FINAL

Combustion 2000
Phase II

DE-AC22-95PC95144--26

Quarterly Progress Report

October 1 - December 31, 1999

Prepared for

Federal Energy Technology Center
Pittsburgh, Pennsylvania

United Technologies Research Center
411 Silver Lane, East Hartford, Connecticut 06108

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Abstract

This report presents work carried out under contract DE-AC22-95PC95144 "Combustion 2000 - Phase II." The goals of the program are to develop a coal-fired high performance power generation system (HIPPS) that is capable of:

- ◊ thermal efficiency (HHV) ≥ 47%
- ◊ NOx, SOx, and particulates ≤ 10% NSPS (New Source Performance Standard)
- ◊ coal providing ≥ 65% of heat input
- ◊ all solid wastes benign
- ◊ cost of electricity ≤ 90% of present plants

Phase I, which began in 1992, focused on the analysis of various configurations of indirectly fired cycles and on technical assessments of alternative plant subsystems and components, including performance requirements, developmental status, design options, complexity and reliability, and capital and operating costs. Phase I also included preliminary R&D and the preparation of designs for HIPPS commercial plants approximately 300 MWe in size.

Phase II, had as its initial objective the development of a complete design base for the construction and operation of a HIPPS prototype plant to be constructed in Phase III. As part of a descoping initiative, the Phase III program has been eliminated and work related to the commercial plant design has been ended. The rescoped program retained a program of engineering research and development focusing on high temperature heat exchangers, e.g. HITAF development (Task 2); a rescoped Task 6 that is pertinent to Vision 21 objectives and focuses on advanced cycle analysis and optimization, integration of gas turbines into complex cycles, and repowering designs; and preparation of the Phase II Technical Report (Task 8). This rescoped program deleted all subsystem testing (Tasks 3, 4, and 5) and the development of a site-specific engineering design and test plan for the HIPPS prototype plant (Task 7).

Work reported herein is from:

- ◊ Task 2.2.4 Pilot Scale Testing
- ◊ Task 2.2.5.2 Laboratory and Bench Scale Activities

Executive Summary

This report represents work carried out under contract DE-AC22-95PC95144 "Combustion 2000: Phase II." The goals of the program are to develop a coal-fired high performance power generation system (HIPPS) that is capable of:

- ◊ ≥ 47% thermal efficiency (HHV)
- ◊ NOx, SOx, and particulates ≤ 10% NSPS
- ◊ coal providing ≥ 65% of heat input
- ◊ all solid wastes benign
- ◊ cost of electricity ≤ 90% of present plant

Work reported in this report is from Task 2.2 HITAF Air Heaters.

Task 2.2.4 Pilot Scale Testing

Analysis of the results of the September 13-20, 1999 SFS tests are presented. The fuel fired in this run was a new eastern Kentucky bituminous coal with a higher ash fusion temperature than any other previously fired in the SFS.

The December SFS tests were not analyzed in time for this report and will be presented subsequently. Some of the goals and operating conditions are discussed.

Salient points:

- The September SFS test was ended at 107 hours instead of the planned 200-hour coal-fired test because of a ruptured air line.
- The September test was designed to evaluate the SFS operation on a different coal with a high ash fusion temperature and to evaluate further the RAH panel and increase the hours of exposure to slagging conditions.
- The slag screen operated as designed although there was significant mass loss to the tubes. This did not require a change since the December test fired Ill#6 which tends to build up a slag layer on the tubes.
- Five uncooled tubes of a ferritic ODS alloy were placed in front of the CAH tube bank. Following the September test, two of these tubes were removed for testing and evaluation of the ash corrosion.
- The three central Monofrax M tiles operated as before. That is they survived the corrosion/erosion of the high temperature test but developed minor cracks on cooling.
- There appears to be a gradual decrease in RAH heat recovery with time. While the reasons are not known, present speculation is focusing on the changes in thermal conductivity and/or emissivity of the tiles. However a change in the emissivity of the high density furnace refractory is also possible.

- The December SFS test was specifically designed to test a new tile material, sintered chromia-alumina supplied by Kyocera. The test was successful showing insignificant corrosion after 200 hours of Ill#6 firing. A crack did occur on cool down and will be further analyzed.
- The total operating hours for the RAH and CAH are shown in the table.

Summary of Operating Hours for the SFS, CAH Tube Bank, and RAH Panel Through December 1999

	Natural Gas Firing, hr	Coal/Lignite Firing, hr	Total Operation, hr
Slagging Furnace System	1686	1181	2867
CAH Tube Bank	1371	1148	2519
RAH Panel	1187	1101	2288

Introduction

The High Performance Power Systems (HIPPS) electric power generation plant integrates a combustion gas turbine and heat recovery steam generator (HRSG) combined cycle arrangement with an advanced coal-fired boiler. The unique feature of the HIPPS plant is the partial heating of gas turbine (GT) compressor outlet air using energy released by firing coal in the high temperature advanced furnace (HITAF). The compressed air is additionally heated prior to entering the GT expander section by burning natural gas. Thermal energy in the gas turbine exhaust and in the HITAF flue gas are used in a steam cycle to maximize electric power production. The HIPPS plant arrangement is thus a combination of existing technologies (gas turbine, heat recovery boilers, conventional steam cycle) and new technologies (the HITAF design including the air heaters, and especially the heater located in the radiant section).

The HITAF provides heat to the compressor outlet air using two air heaters, a convective air heater (CAH), and a radiant air heater (RAH). The HITAF is a slagging furnace which contains the radiant air heater, as well as waterwalls and steam drum for the high pressure (HP) steam system. Hot flue gas leaving the HITAF furnace passes over the CAH prior to entering a heat recovery steam generator (HRSG). Hot exhaust gas from the gas turbine is ducted to another HRSG in a typical combined cycle arrangement. The HITAF, gas turbine and HRSGs are configured to achieve the required high efficiency of the HIPPS plant.

The key to the success of the concept is the development of integrated combustor/air heater that will fire a wide range of US coals with minimal natural gas and with the reliability of current coal-fired plants. The compatibility of the slagging combustor with the high temperature radiant air heater is the critical challenge.

Task 2.2.4 – Pilot-Scale Testing

Pilot-scale activities this past quarter involved SFS modifications and repairs, replacement of ceramic tiles on the RAH panel, and completion of a 200-hr coal-fired SFS test in December.

Description of Pilot-Scale SFS

Exhibit 2-1 (exhibits follow text) is a simplified illustration of the overall slagging furnace system. There have been no changes to the exhibit in the past quarter. Instrumentation work this past quarter focused on routine maintenance and calibration of SFS components. Other activities were limited to miscellaneous maintenance items in support of overall SFS operation and preparation for CAH sootblowing during future SFS tests.

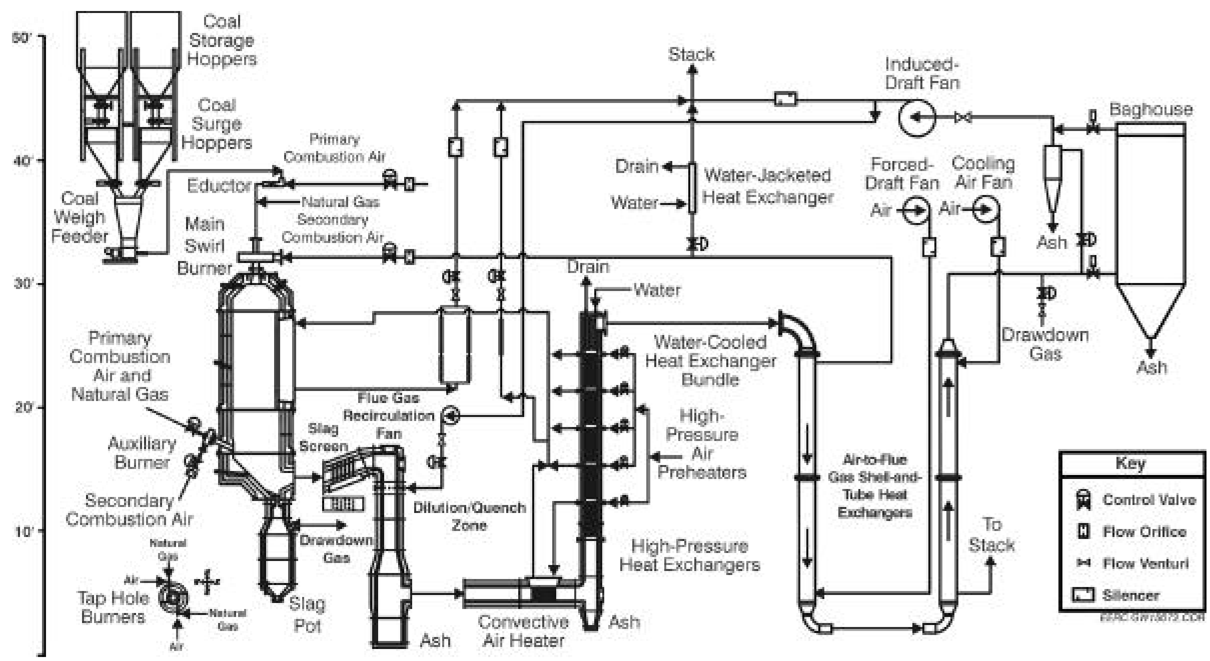

Exhibit 2-1
Combustion 2000 Slagging Furnace and Support Systems

The September SFS test was terminated after completion of only 107 hours of a planned 200-hour coal-fired test because of a ruptured high-temperature/low-pressure process air line supporting the RAH panel. Some air flow through the RAH was still possible, so no extraordinary measures, such as backflushing the RAH with nitrogen, were necessary. Coal firing was terminated, and a normal cooldown on natural gas took place. The ruptured air line, which operates at a temperature and pressure of 1300°F (705°C) and 150 psig (10 bar), was replaced.

Fuel Feed System

Coal feed system leaks were not observed during the September or December test periods, suggesting that the nitrogen-purged mechanical seals are a definite improvement over the Teflon seals originally supplied by the manufacturer.

Slagging Furnace

The pilot-scale slagging furnace design is intended to be as fuel-flexible as possible, with maximum furnace exit temperatures of 2700° to 2900°F (1483° to 1593°C) to maintain the desired heat transfer to the RAH panel and slag flow. The furnace has a nominal firing rate of 2.5 MMBtu/hr (2.6×10^6 kJ/hr) and a range of 2.0 to 3.0 MMBtu/hr (2.1 to 3.2×10^6 kJ/hr) using a single burner. The design is based on Illinois No. 6 bituminous coal (11,100 Btu/lb or 25,800 kJ/kg) and a nominal furnace residence time of 3.5 s. Flue gas flow rates range from roughly 425 to 645 scfm (12.0 to 18.6 m^3/min), with a nominal value of 530 scfm (15 m^3/min), based on 20% excess air. Firing a subbituminous coal or lignite increases the flue gas volume, decreasing residence time to roughly 2.6 s. However, the high volatility of the low-rank fuels results in high combustion efficiency (>99%). The EERC oriented the furnace vertically (downfired) and based the burner design on that of a swirl burner used on two smaller EERC pilot-scale pulverized coal- (pc)-fired units (600,000 Btu/hr [633,000 kJ/hr]). Slagging furnace internal dimensions are 47 in. (119 cm) in diameter by roughly 16 ft (4.9 m) in total length.

The vertically oriented furnace shell was designed to include four distinct furnace sections. The top section of the furnace supports the main burner connection, while the upper-middle furnace section provides a location for installation of the RAH panels. The lower-middle furnace section supports the auxiliary gas burner; the bottom section of the furnace includes the furnace exit to the slag screen as well as the slag tap opening. Flue gas temperature measurements are made using two Type S thermocouples protruding 1 in. (2.5 cm) into the furnace through the refractory wall and three optical pyrometers (flame, flue gas along the furnace wall near the RAH panel, and flue gas at the furnace exit). Furnace temperature is also measured using thermocouples located at the interface between the high-density and intermediate refractory layers as well as between the intermediate and insulating refractory layers. A pressure transmitter and gauges are used to monitor static pressures in order to in turn monitor furnace performance. These data (temperatures and pressures) are automatically logged into the data acquisition system and recorded manually on data sheets on a periodic basis as backup.

The slag tap is intended to be as simple and functional as possible. To that end, the design is a simple refractory-lined hole in the bottom of the furnace. The diameter of the slag tap is nominally 4 in. (10 cm), with a well-defined drip edge. A two-port natural gas-fired tap hole burner is used to maintain slag tap temperature for good slag flow. To minimize heat losses, slag is collected in an uncooled, dry container with refractory walls. When the slag tap has plugged in the past year, the plug was typically removed on-line after a switch was made to natural gas firing for a short period of time (2 hours) in the main burner. More recently, an approach has been developed and personnel safety equipment acquired to permit the removal of slag tap plugs on-line while coal is fired. During the September test period, both approaches were used to clear slag tap plugs.

The refractory walls in the slagging furnace are composed of three layers of castable refractory. They consist of an inner 4-in. (10.2-cm) layer of high-density (14-Btu-in./ft^2°F-hr or 2.0-W/m-K) slag-resistant material, 4 in. (10.2 cm) of an intermediate refractory (4.0 Btu-in./ ft^2°F-hr or 0.6 W/m-K), and a 3.25-in. (8.3-cm) outer layer of a low-density insulating refractory (1.3 Btu-in./ft^2°F-hr or 0.2 W/m-K). Three refractory layers were selected as a cost-effective approach to keeping the overall size and weight of the system to a minimum while reducing slag corrosion and heat loss. Table 2-1 summarizes properties for refractories used in the SFS. The condition of the high-density refractory in all sections of the furnace appeared to be excellent following the test completed in September 1999.

Main and Auxiliary Burners

The main burner is natural gas- and pulverized fuel-capable. The basic design is an International Flame Research Foundation (IFRF)-type adjustable secondary air swirl generator, which uses primary and secondary air at approximately 15% and 85% of the total air, respectively, to adjust swirl. Increasing swirl to provide flame stability and increased carbon conversion can also affect the formation of NO_x. Carbon conversion has been >99% when bituminous and subbituminous coal and lignite are fired. High carbon conversions can be obtained at low swirl settings because of the high operating temperature and adequate residence time. Combustion air flow rates through the main burner range from about 400 to 600 scfm 11 to 17 m^3/min), depending on furnace firing rate and the fuel type (bituminous, subbituminous, or lignite) fired.

Table 2-1
Refractory Properties

Refractory:	Plicast Cement-Free 99V KK/99V[1]	Plicast Cement-Free 98V KK/98V[1]	Plicast Cement-Free 96V KK/96V[1]	Narco Cast 60	Plicast LWI-28	Plicast LWI-20	Harbison-Walker 26
Function	High density	High density	High density	High density	Insulating	Insulating	Insulating
Service Limit, °F	3400	3400	3300	3100	2800	2000	2600
Density, lb/ft^3	185	185	185	145	80	55	66
K, Btu-in./ft^2 °F-hr @ 2000°F	14.5	14.5	14.0	6.5	4.0	NA[2]	2.2
K, Btu-in./ft^2 °F-hr @ 1500°F	14.7	14.7	14.2	6.0	3.0	1.7	1.9
K, Btu-in./ft^2 °F-hr @ 1000°F	15.5	15.5	15.0	5.6	2.7	1.3	1.7
Hot MOR[3] @ 2500°F, psi	650	750	1400	NA	NA	NA	NA
Hot MOR @ 1500 °F, psi	–	–	2000	1000	250	100	110
Cold Crush Strength @ 1500 °F, psi	–	–	10000	NA	750	400	350
Typical Chemical Analysis, wt% (calcined)							
Al_2O_3	99.6	98.6	95.5	62.2	54.2	39.6	53.8
SiO_2	0.1	1.0	3.8	28.0	36.3	31.5	36.3
Fe_2O_3	0.1	0.1	0.1	1.0	0.8	5.4	0.5
TiO_2	0.0	0.0	0.0	1.7	0.5	1.5	0.6
CaO	0.1	0.1	0.1	2.8	5.7	19.5	7.2
MgO	0.0	0.0	0.0	0.1	0.2	0.8	0.2
Alkalies	0.2	0.2	0.2	0.2	1.5	1.4	1.4

[1] The “KK” designation indicates the presence of fibers that promote dewatering during curing.

[2] Not applicable.

[3] Modulus of rupture.

An auxiliary gas burner (850,000 Btu/hr or 896,750 kJ/hr) is located near the furnace exit to control furnace exit temperature, ensuring desired slag flow from the furnace and the slag screen. This auxiliary burner is used to compensate for heat losses through the furnace walls, sight ports, and RAH test panel. Use of the auxiliary gas burner is beneficial during start-up to reduce heatup time and to prevent slag from freezing on the slag screen when the switch is initially made to coal firing.

Radiant Air Heater Panel

A key design feature of the furnace is accessibility for installation and testing of an RAH panel. The furnace will accept a panel with a maximum active size of 1.5 × 6.4 ft (0.46 × 1.96 m). This size was selected on the basis of panel-manufacturing constraints identified by UTRC as well as a desire to minimize furnace heat losses. Flame impingement on the RAH panel is not necessarily a problem. Process air for the RAH panel is provided by an existing EERC air compressor system having a maximum delivery rate of 510 scfm (14.4 m^3/min) and a maximum stable delivery pressure of 275 psig (19 bar). Backup process air is available from a smaller compressor at a maximum delivery rate of 300 scfm (8.5 m^3/min) and pressure of <100 psig (<7 bar). A tie-in to an existing nitrogen system is also available as a backup to the existing air compressor system. In the event of a failure of inlet process air piping, a backflow emergency piping system was installed so that overheating of the RAH panel could be avoided. UTRC designed and fabricated the RAH test panel.

Slag Screen

The slag screen design for the pilot-scale SFS is the result of a cooperative effort between EERC, UTRC, and PSI personnel. The primary objective for the pilot-scale slag screen is to reduce the concentration of ash particles entering the convective air heater (CAH). The walls of the slag screen consist of two refractory layers. The inner, high-density layer is a Plicast Cement-Free 98V with an outer insulating layer of Harbison-Walker Castable 26. The high-density refractory is 2.25 in. (5.7 cm) thick in the sidewalls and 4 in. (10.2 cm) thick in the roof and floor of the slag screen. The insulating refractory is 3.75 in. (9.5 cm) thick in the sidewalls, roof, and floor. A Plicast LWI-28 refractory was used around the sight ports in the wall of the slag screen. Properties for the high-density and insulating refractories selected for use in the slag screen are summarized in Table 2-1. Water-cooled surfaces were installed inside of the refractory tubes to cool the tubes and reduce the erosion/corrosion observed during shakedown tests. Specific details concerning slag screen modifications and performance this quarter are addressed later in this report.

Dilution/Quench Zone

The dilution/quench zone design was a cooperative effort between the EERC and UTRC. It is refractory-lined and located immediately downstream of the slag screen and upstream of the CAH duct. It is oriented vertically and has a circular cross-sectional 1.17-ft (0.36-m) diameter in the area of the flue gas recirculation (FGR) nozzles, expanding to 2 ft (0.6 m) below them to provide adequate residence time within duct length constraints. The duct section containing the flue gas recirculation nozzles is a spool piece to accommodate potential changes to the size, number, and orientation of the flue gas recirculation nozzles.

Routine cleaning of the dilution/quench zone has been required during each weeklong bituminous and subbituminous coal-fired test. In order to monitor and document the slag deposition in the dilution/quench zone, a pressure transmitter is used to monitor and record differential pressure. On the basis of observations made during an August 1998 test and the frequent cleaning required, the EERC modified the spool piece section of the dilution/quench zone. The specific modification involved the addition of a water-cooled wall around the FGR nozzles. This water-cooled wall appears to embrittle the slag deposits that form in this area, making them more prone to spontaneous shedding and generally easier to remove on-line. Performance observations during the September test are summarized later in this report.

Convective Air Heater

The CAH design was a cooperative effort between the EERC and UTRC. The flue gas flow rate to the CAH tube bank has been calculated to range from 3553 to 4619 acfm at 1800°F (101 to 131 m^3/min at 982°C). A rectangular inside duct dimension of 1.17 ft^2 (0.11 m^2) results in a flue gas approach velocity of 50 to 73 ft/s (15 to 22 m/s) to the CAH. The CAH originally consisted of twelve 2-in. (5-cm)-diameter tubes installed in a staggered three-row array. The first five tubes in the flue gas path were uncooled ceramic material, with the remaining seven tubes cooled by heated air. The uncooled ceramic tubes were replaced in May 1998 with uncooled stainless steel tubes because they were repeatedly damaged when the tube bank was removed from the duct.

In September 1998, the uncooled tubes were again replaced. The replacement tubes represented three high-temperature alloy types (Incoloy MA956, Incoloy MA956HT, and PM2000) and three pipe sizes (1.5-in. [3.8-cm] Schedule 80, 1-in. [2.5-cm] Schedule 40, and 0.75-in. [1.9-cm] Schedule 40, respectively). Exhibit 2-2 illustrates the original position, size, and alloy type for the five uncooled tubes. At the request of UTRC two of these uncooled alloy tubes were removed from the CAH tube bank following the September test and returned to UTRC for characterization. The tubes removed from the CAH represent the alloys designated Incoloy MA956HT and Incoloy MA956. Replacement tubes were fabricated using stainless steel.

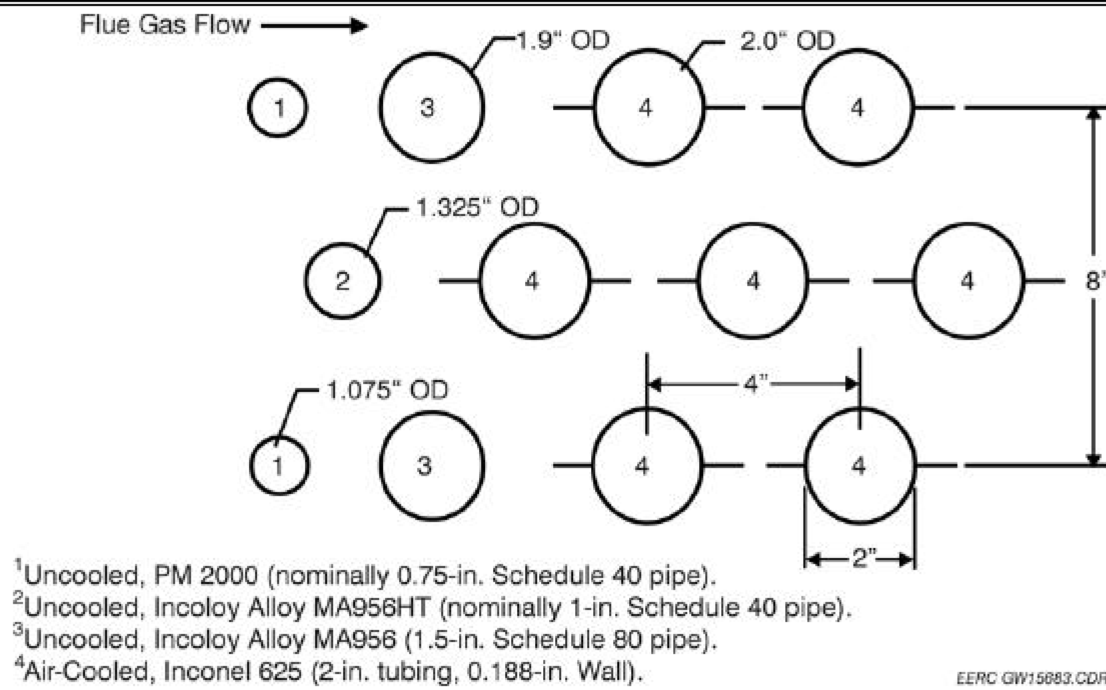

Exhibit 2-2
Illustration of the Uncooled Tubes in the CAH Tube Bank

Emission Control

A pulse-jet baghouse is used for final particulate control on the pilot-scale SFS. The baghouse design permits operation at both cold-side (250° to 400°F, 121° to 205°C) and hot-side (600° to 700 °F, 316° to 371°C) temperatures. The primary baghouse chamber and ash hopper walls are electrically heated and insulated to provide adequate temperature control to minimize heat loss and avoid condensation problems on start-up and shutdown. The main baghouse chamber was designed with internal angle iron supports to handle a negative static pressure of 20 in. W.C. (37 mm Hg).

During the past quarter, a single tube sheet was used, permitting the installation of 36 bags arranged in a six-by-six array. Bag dimensions are nominally 6 in. (15.2 cm) in diameter by 10 ft (3.0 m) in length, providing a total filtration area of (565 ft^2 [52.5 m^2]). The bag type being used at this time is a 22-oz/yd^2 (747-g/m^2) woven glass bag with a polytetrafluoroethylene (PTFE) membrane. Pulse cleaning of the bags was accomplished on-line in September using a reservoir pulse-air pressure of nominally 60 psig (4.1 bar). Baghouse performance observations during the September test are summarized later in this report.

Instrumentation and Data Acquisition

The instrumentation and data acquisition components for the pilot-scale SFS address combustion air, flue gas, process air, process water, temperatures, static and differential pressures, and flow rates. The data acquisition system is based on a Genesis software package and three personal computers. Two sets of flue gas instrumentation (oxygen, carbon dioxide, carbon monoxide, sulfur dioxide, and nitrogen species) are dedicated to support the operation of the SFS. Flue gas is transferred from the sample point through a heated filter and sample line to the sample conditioner before it reaches the analyzers. Flue gas is routinely sampled in the slag screen at the furnace exit and the exit of the baghouse. Total flue gas flow rate through the SFS is measured using a venturi. No instrumentation work was completed this past quarter other than routine maintenance and calibration.

Pilot-Scale SFS Activities This Quarter

The pilot-scale SFS was fired on natural gas and an eastern Kentucky coal from the Prater Creek mine for 107 hours during the period September 12 – 20 (SFS-RH10-0699). Because the results from that test were not available for inclusion in the July through September quarterly report, they are presented here. The purpose of the test was to further evaluate the RAH panel and increase the number of hours of exposure to slagging furnace conditions following its reassembly and installation in early January. Data evaluation and sample analysis have been completed. Therefore, this report summarizes the results and observations for the September test as well as SFS maintenance and modification activities this past quarter. In addition, a 200-hour coal-fired SFS test was completed in December. However, results from that test are not available for inclusion in this report and will be summarized in a subsequent quarterly report.

Fuel Feed System

Nominal feed rates during the September tests were 150 to 160 lb/hr (68 to 73 kg/hr). Adjustments to coal feed rate were made in order to maintain a flue gas temperature near the RAH tile surfaces and furnace exit of 2900°F (1593°C). Typically, the flue gas temperature near the RAH tile surfaces and furnace exit is controlled at 2800°F (1538°C). However, during the September test, a higher temperature was used because of the higher ash fusion temperature of the fuel ash and the apparent ineffectiveness of limestone addition to reduce slag viscosity. Exhibit 2-3 illustrates the coal feed rate data for the September test. During the test, the coal feed rate was quite stable except for a few minor spikes (high and low) associated with coal hopper refill cycles.

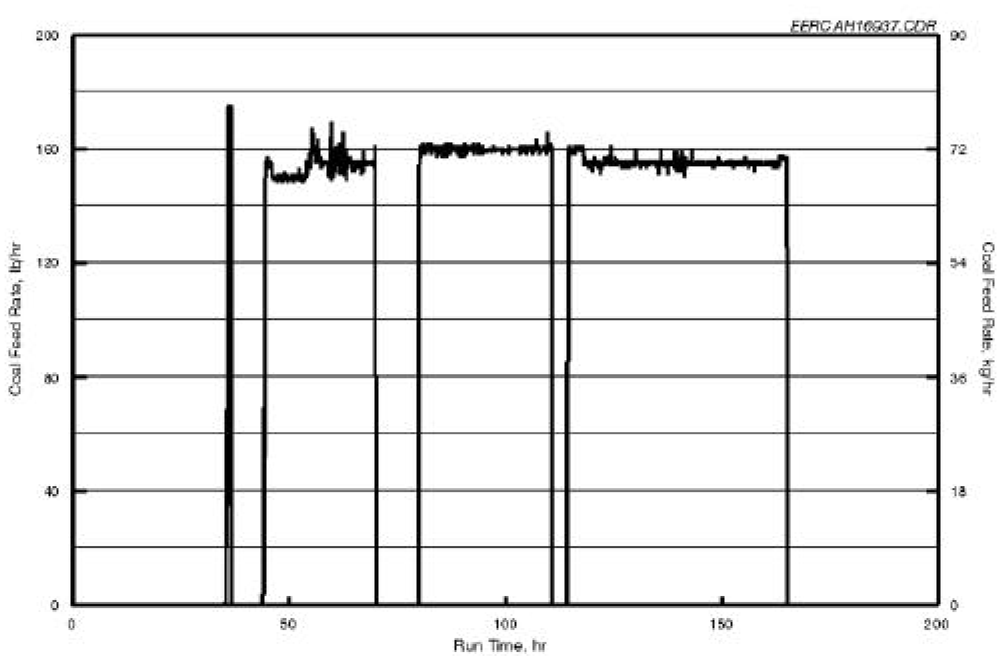

Exhibit 2-3
Coal Feed Rate Versus Run Time for the September Test, SFS-RH10-069930

The coal weigh hopper was filled with coal prior to initiating coal feed. Because of the fluid nature of dry pulverized coal and the negative static pressure at the coal feed screw, an unmeasured quantity of coal was drawn into the furnace through the stationary screws. This resulted in a temporary positive static pressure in the furnace and high temperatures in the region of the slag screen and quench zone, as well as in the furnace itself. Steam was generated in the quench zone water-cooled jacket, and a small leak developed in the water exit line. While this coal feed phenomenon has been observed in the past, the addition of purge air in the coal weigh hopper to keep coal dust out of the seals at the bottom of the hopper contributed to a "fluidized-bed" effect. This resulted in a more dramatic upset than has been seen previously. During the December test, the coal feed auger discharge opening was sealed during the first coal weigh hopper fill cycle and the problem was avoided.

Tables 2-2 and 2-3 summarize analytical results for all of the coals that had been fired in the SFS through September. They include Illinois No. 6 bituminous, Kentucky bituminous, Prater Creek bituminous, and Rochelle subbituminous coals and Coal Creek Station (CCS) and Milton R. Young Station (MRYS) lignites. The analyses of the composite Prater Creek (eastern Kentucky) coal fired in September indicated that the as-fired fuel contained 2.0 wt% moisture, 4.7 wt% ash, and 0.8 wt% sulfur. The heating value was 14,167 Btu/lb (32,921 kJ/kg) on an as-fired basis. Coal ash was analyzed for ash fusion properties under oxidizing conditions. Results indicate a softening temperature of 2483°F (1362°C) and a fluid temperature of 2593°F (1423°C). The fluid temperature of this coal ash was comparable to the eastern Kentucky fuel previously fired. However, the use of limestone addition was not an effective mitigation step to controlling slag screen and slag tap plugging.

Dry-sieve analysis indicated that the pulverized Prater Creek coal was nominally 60 wt% =200 mesh (74 microns [µm]) in September. This is a slightly larger size distribution than was seen for the eastern Kentucky coal previously fired, and definitely larger than the desired 70 wt% =200 mesh (74 μm). The carbon content of the fly ash collected in the baghouse was 0.59 wt%, indicating good combustion efficiency.

X-ray fluorescence (XRF) analysis results for the various ashed fuels are summarized in Tables 2-2 and 2-3 and reported as oxides. The Prater Creek coal fired in September differed in several ways from the Kentucky coal fired previously. The silica and alumina contents of the ash were lower, while the iron, calcium, and sulfur contents were higher. The ash fusion temperatures were as high as, if not higher than, those observed for coals fired in the SFS to date, although it is not clear exactly why they were so high, because coals with lower silica and alumina contents typically have lower ash fusion temperatures. The impact of the relatively high Prater Creek coal ash fusion temperatures are discussed in a later section of this report with respect to the performance of the slag screen and slag tap.

Table 2-2
Results of Coal and Coal Ash Analysis for Coal-Fired Slagging Furnace Tests[1]

	Illinois No. 6 Bituminous Coal	Kentucky Bituminous Coal	Prater Creek Bituminous Coal	Rochelle Subbituminous Coal
Proximate Analysis, wt%				
Moisture	4.4–10.3	2.3–2.5	2.0	21.6–24.3
Volatile Matter	35.9–39.5	38.2–38.7	38.7	35.6–37.4
Fixed Carbon	43.3–46.3	54.7–54.9	54.5	35.8–36.7
Ash	10.6–11.5	3.9–4.7	4.7	4.3–4.7
Ultimate Analysis, wt%				
Hydrogen	4.8–5.8	5.2–5.5	5.4	6.1–6.4
Carbon	61.6–64.9	77.5–78.2	78.3	53.0–55.2
Nitrogen	0.8–1.6	1.8	2.3	0.6–0.7
Sulfur	3.2–4.1	0.8–1.0	0.8	0.3
Oxygen	14.2–17.6	9.6–9.7	8.4	32.9–33.4
Ash	10.6–11.5	3.9–4.7	4.7	4.3–4.7
Heating Value, Btu/lb	11,015–11,658	13,861–14,120	14,167	9021–9328
Percent as Oxides, wt%				
SiO_2	50.2–53.9	42.5–44.8	38.4	26.7–27.1
Al_2O_3	19.8–21.2	28.9–29.8	25.0	15.5–16.3
Fe_2O_3	13.6–16.0	13.7–14.5	22.5	6.3–6.6
TiO_2	0.9	1.1	1.0	1.2–1.4
P_2O_5	0.1–0.2	0.1	0.1	0.7–0.9
CaO	3.0–3.6	1.9–2.8	3.8	21.6–24.3
MgO	1.5–2.0	2.2–2.4	2.1	6.7–6.9
Na_2O	1.1–1.4	1.1–1.3	0.3	1.5
K_2O	1.9–2.1	2.7–3.0	2.2	0.1–0.4
SO_3	2.5–4.0	2.4–3.8	4.6	15.6–17.0
Ash Fusion Temp., °F				
Initial	2315–2361	2398–2577	2483	2202–2295
Softening	2342–2417	2440–2603	2490	2205–2308
Hemisphere	2392–2448	2474–2621	2544	2214–2311
Fluid	2491–2534	2588–2684	2593	2221–2325
Sieve Analysis				
Screen Mesh Size	Weight Percent Retained			
100	1.8–25.2	8.1–11.4	13.6	7.6–8.8
140	0–14.9	12.9–13.9	15.1	14.2–15.4
170	0–14.9	NA[2]	NA	NA
200	9.6–13.5	11.4–13.5	12.4	14.3–14.4
230	0–16.2	8.7–9.4	8.3	8.4–9.1
270	0.5–14.6	0.7–1.6	0.8	2.0–5.6
325	7.4–14.7	11.9–12.7	10.9	4.8–11.6
400	0–4.7	NA	NA	NA
Pan	29.7–57.8	41.2–42.6	38.8	39.7–43.4
Total %	99–100.2	99.9–100.1	99.9	98.6–100.6

[1] As-fired basis

Table 2-3
Results of Lignite and Lignite Ash Analysis for Lignite-Fired Slagging Furnace Tests[1]

	Coal Creek Station Lignite	Milton R. Young Station Lignite
Proximate Analysis, wt%		
Moisture	31.6–37.9	33.8–37.1
Volatile Matter	29.4–31.5	30.4–32.1
Fixed Carbon	26.4–26.8	26.9–27.9
Ash	6.3–10.2	5.6–6.2
Ultimate Analysis, wt%		
Hydrogen	6.4–6.8	7.0–7.2
Carbon	38.5–40.9	41.1–43.4
Nitrogen	0.6	0.6
Sulfur	0.5–0.7	0.7–0.9
Oxygen	41.1–47.3	42.1–44.9
Ash	6.3–10.2	5.6–6.2
Heating Value, Btu/lb	6300–6708	6933–7144
Percent as Oxides, wt%		
SiO_2	31.8–35.5	11.2
Al_2O_3	11.7–12.0	8.6
Fe_2O_3	6.4–8.0	13.2
TiO_2	0.5	0.2
P_2O_5	0.3	0.1
CaO	17.0–18.7	21.3
MgO	6.5–7.0	7.3
Na_2O	2.9–3.2	11.7
K_2O	1.3	0.2
SO_3	16.0–19.0	26.2
Ash Fusion Temp., °F		
Initial	2170–2188	2370–2371
Softening	2181–2196	2381–2384
Hemisphere	2189–2203	2384–2387
Fluid	2196–2219	2392–2428
Sieve Analysis		
Screen Mesh Size	Weight Percent Retained	
100	6.4–10.3	14.9
140	12.3–13.8	15.7
170	NA[2]	4.6
200	11.9–12.3	8.5
230	3.7–8.5	NA
270	6.2–10.2	3.1
325	6.4–6.5	14.9
400	NA	NA
Pan	41.5–48.2	38.2
Total %	98.3–99.9	99.9

[1] Lignite analysis is presented on an as-fired basis.
[2] Not available.

Slagging Furnace Operation

The slagging furnace heating rate during the September test period was limited to 100°F/hr (56°C/hr) while natural gas was fired, as recommended for the RAH panel by UTRC. When the furnace reached normal operating temperature (2800°F, 1538°C), the main burner was switched from natural gas to coal firing. The coal-firing rate was 2.1 to 2.3 MMBtu/hr (2.2 to 2.4 × 10^6 kJ/hr) with an auxiliary burner firing rate of 0.6 to 0.7 MMBtu/hr (0.63 to 0.74 × 10^6 kJ/hr). These coal-firing conditions were maintained for 107 hours in an attempt to maintain a furnace flue gas temperature near the RAH panel of 2900°F (1595°C). This temperature measurement was made using an optical pyrometer with secondary measurements using Type S thermocouples. A summary of furnace and slag screen temperatures is presented as a function of run time in Exhibit 2-4. Corresponding slagging furnace firing rate data are summarized in Exhibit 2-5.

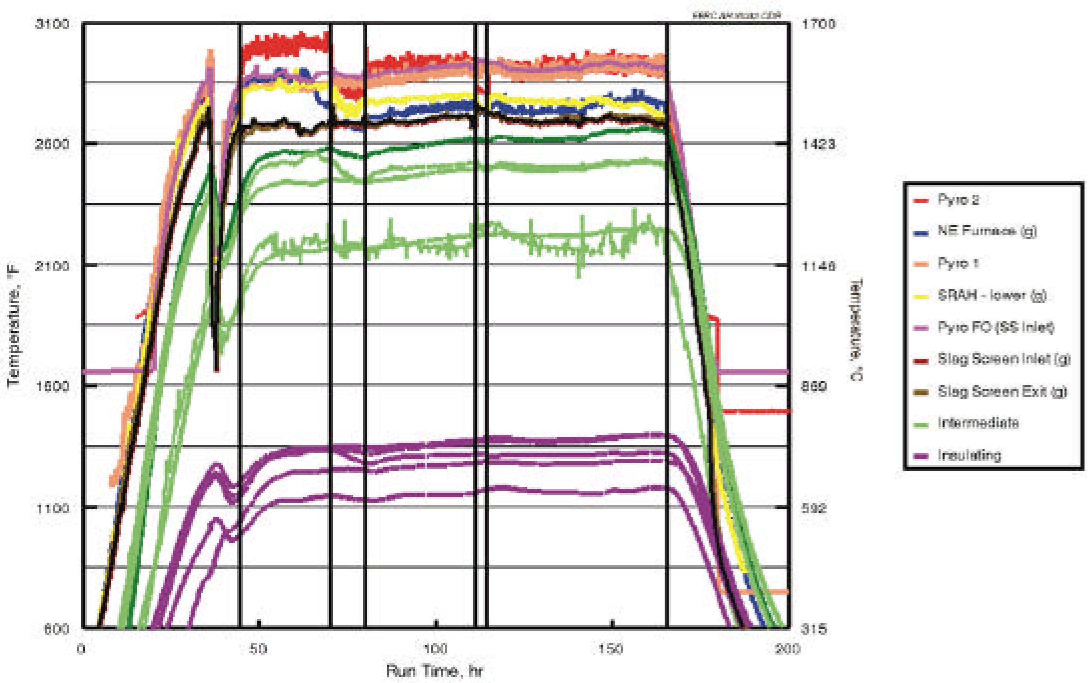

Exhibit 2-4
Furnace and Slag Screen Temperatures Versus Run Time for the September Test, SFS-RH10-0699

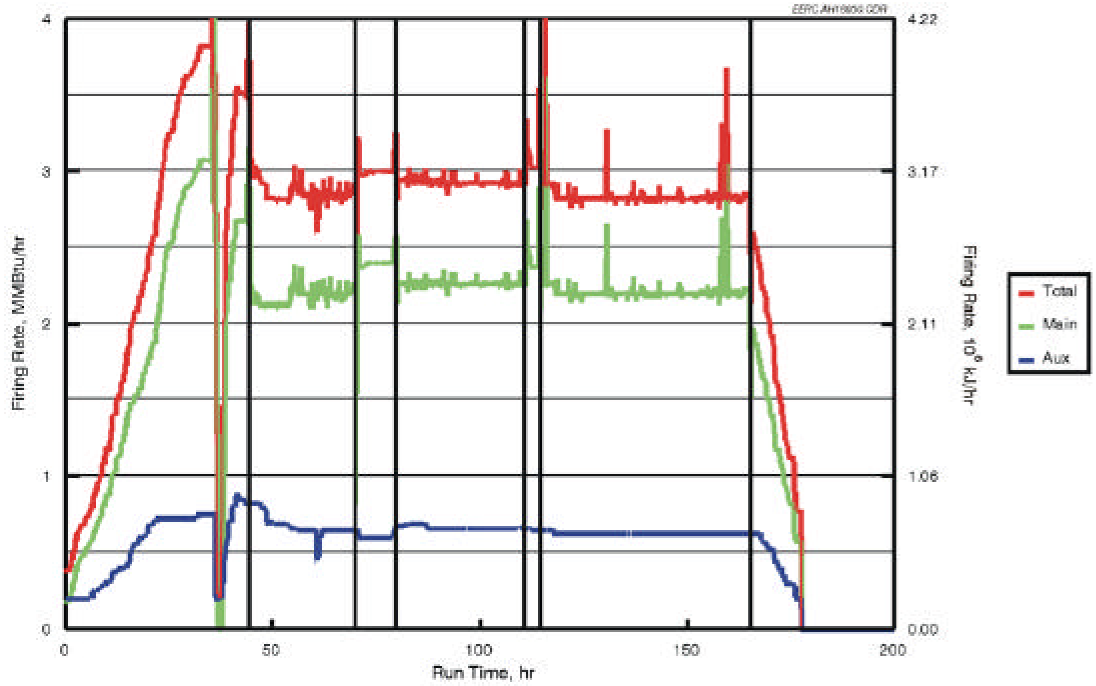

Exhibit 2-5
Slagging Furnace Firing Rate Versus Run Time for the September Test, SFS-RH10-0699

During the September test, the main burner swirl setting was maintained at about 20% during coal firing. After 10 hours of coal firing, limestone feed was initiated at 0.5 lb/hr in an attempt to lower the fluid temperature of the slag in the slag screen/slag tap. In addition, the temperatures in the lower furnace and slag pot were increased in an effort to keep the slag flowing. While this was immediately effective, the continued addition of limestone seemed to have no impact later, and the slag tap plugged after 26 total hours to the point where firing was switched from coal to natural gas. The slag pot was removed, and the slag tap plug cleared. Coal feed was restarted when the slag pot approached furnace exit temperature.

The second period of coal firing lasted 30 hours. This time, the slag pot was removed and the slag tap cleared without switching to natural gas; this was effective, except that the slag tap burners tripped out and could not be restarted. This necessitated a second period of natural gas firing until combustion in the slag tap burners could be maintained. The third and final period of coal firing lasted 51 hours without limestone addition, with no further problems with the slag tap or slag tap burners. With this particular fuel, after an initial period, limestone addition was not an obvious benefit and may have promoted slag tap plugging. Unfortunately, a leak was discovered in the high-temperature/low-pressure piping at the inlet to the RAH. Since this reduced the volume of process air available to the RAH, and because the leak was gradually increasing, the decision was made to proceed with a normal cooldown on natural gas. The process air flow was monitored closely during the cooldown to assure a reasonable cooldown rate in the RAH panel. The total furnace-firing rate (main plus auxiliary burners) ranged from 2.8 to 2.9 MMBtu/hr (2.9 to 3.1 × 10^6 kJ/hr). The main burner-firing rate ranged from 2.1 to 2.3

MMBtu/hr
(2.2 to 2.4 × 10^6 kJ/hr), accounting for about 77% of the total energy input. The resulting flue gas temperature near the furnace wall/RAH panel was 2850° to 2950°F (1566° to 1621°C).

Furnace refractory temperatures ranged from 1130° to 1410°F (610° to 766°C) for the hot side of the insulating refractory to as high as 2550°F (1399°C) for the cold side of the high-density refractory. Compared to the April 1999 test period with the eastern Kentucky coal, the insulating refractory temperatures were 110°F (61°C) higher, and high-density refractory temperatures were 120°F (67°C) higher. These higher refractory temperatures were the result of a higher firing rate in September, 2.8 to 2.9 MMBtu/hr (2.9 to 3.1 × 10^6 kJ/hr) versus 2.7 to 2.8 MMBtu/hr (2.8 to 2.9 × 10^6 kJ/hr) in April. The higher firing rate and resulting furnace temperatures in September were necessary to keep the furnace exit temperature above the fluid temperature of the slag. It was increased during the run in an attempt to mitigate slag tap plugging.

The high-density refractory lining the furnace was found to be in excellent condition following the September test. The new slag screen inlet design, with rounded edges on the sides, appears to have minimized erosion, in spite of a high auxiliary burner firing rate. However, as a result of further densifying/shrinkage of the high-density refractory layer in the furnace, it was necessary to add 2 in. (5 cm) of high-density refractory to the top of the main furnace section prior to the December test in order to avoid exposing the intermediate refractory layer to furnace operating temperatures. Exhibit 2-6 presents a photograph of the interior of the furnace showing the new refractory layer at the top of the main furnace section, the continued darkening of the furnace walls seen following each coal-firing period, and the RAH tiles installed prior to the December test.

EERC GW16898.CDR

Exhibit 2-6
Photograph of Furnace Interior Prior to the December Test, SFS-RH11-0799

Main and Auxiliary Burners

The main and auxiliary burners performed well during the September test. As previously stated, the main burner swirl was maintained at about 20%, while the auxiliary burner swirl setting was 80%–100%. Carbon efficiency for this bituminous coal was 99.4% or greater because of the high furnace operating temperature and residence time. On the basis of slagging furnace operating experience, the EERC intends to continue minimum main burner swirl as necessary to establish a stable flame, to establish uniform temperatures over the length of the furnace, and to minimize NO_x emissions. Auxiliary burner firing is adjusted as necessary to maintain desired slag screen inlet temperatures, but will be minimized whenever possible.

Slag Screen

No changes were made to the slag screen between the refractory cure in August and the September test; the current slag screen configuration is three rows of three tubes each. Slag screen flue gas temperatures during the September test with the Prater Creek coal were typically 2670° to 2710°F (1466° to 1488°C) at the inlet and 2660° to 2725°F (1460° to 1496°C) at the outlet. Slag screen operating temperature is selected on the basis of ash fusion data for the fuel to be fired. The EERC tries to operate the slag screen at flue gas temperatures of 100°to 200°F (56° to 112°C) above the fluid temperature of the fuel ash to ensure slag flow from the slag screen to the slag tap. The ash fluid temperature (under oxidizing conditions) of the composite sample of Prater Creek coal analyzed following the September test period was determined to be 2593°F (1423°C).

The eastern Kentucky coal fired previously caused a dramatic increase in slag screen differential pressure, necessitating the use of limestone to alter the slag chemistry and lower the ash fusion temperature. The limestone feed system was in place for the September test in anticipation of similar problems in the slag screen. Slag screen differential pressure was not a problem during the September test, but limestone addition at a feed rate of about 0.5 lb/hr (225 g/hr) was initiated when the slag tap began to plug. Within 20 minutes, the slag tap opened up considerably, although over the next 15 hours, the slag tap gradually plugged off again, requiring a switch to natural gas firing to remove the slag pot and rod out the slag tap. Testing later in the run showed no effect of limestone addition on slag tap performance, and limestone addition was discontinued. There was no limestone addition during the final 51 hours of coal firing, with no problematic plugging of the slag tap. EERC personnel believe that maintaining a slag tap temperature of greater than 2700°F (1482°C) was critical to keeping the slag flowing through the slag tap. Ash fusion analysis of a slag sample collected following the September test determined that the fluid temperature of the slag (in an oxidizing environment) was 2774°F (1524°C). XRF analysis showed some enrichment of the silica, alumina, and iron concentrations along with depletion of alkali components.

Exhibit 2-7 is a photograph of the slag screen inlet following the September test. The first row of slag screen tubes have experienced a substantial loss in mass, measuring only about 0.75 in. (1.9 cm) in diameter at the smallest point, from a starting diameter of 1.5 in. (3.8 cm). However, the December SFS test used Illinois No. 6 coal as the fuel, and EERC experience shows that a layer of slag tends to build up on the tubes with this fuel. Therefore it was not necessary to replace any of the slag screen tubes before the December test period. Operation with the three existing rows of tubes (nine tubes total) has proven satisfactory with the Illinois No. 6 fuel. However, prior to firing a subbituminous coal in

February 2000, the EERC plans to rebuild the slag screen, installing 18 tubes in six rows of three. In addition, EERC personnel will review past experience with subbituminous and lignite fuels in order to select the appropriate size for the water-cooled center tubes.

Exhibit 2-7
Photograph of the Slag Screen Inlet Following the September Test, SFS-RH10-0699

Following the September test, slag and ash samples from system components and piping were collected and weighed in order to prepare a mass balance. A total theoretical ash quantity was calculated (806 lb or 366 kg) on the basis of the total coal feed and the measured ash content of the composite coal sample and the quantity of calcium oxide introduced as limestone. Total slag and ash recovery from the September test was 71% (573 lb or 260 kg). Slag recovery from the furnace, slag pot, and dilution/quench zone represented 45% of the theoretical ash. Additional slag is evident on the furnace wall, on the RAH panel, in the bottom of the furnace, in the slag screen, and in the upper section of the dilution/quench zone. However, this material is not recoverable from the high-density refractory. Because this was the first coal-fired test since the refractory in the furnace bottom was replaced, it is assumed that much of the unrecovered material was absorbed into the new refractory, as has been observed in the past.

Fly ash recovered from other system components (drawdown gas line, CAH duct, process air preheater tubes, tube-and-shell heat exchangers, cyclone, baghouse, and flue gas piping) represented 27% of the theoretical ash for the September test. Nominally 10% to 15% of the ash in the fuels fired in the SFS has been reaching the baghouse. In September, that value was 14% of the total ash/slag.

Dilution/Quench Zone

Slag deposits formed in the vicinity of the FGR nozzles during the September test. As a result, it was necessary to clean the area of the FGR nozzles on a periodic basis. The dilution/quench zone was initially cleaned after nearly 49 hours of coal firing. During the September test, cleaning frequency was more dependent on flue gas temperatures downstream of the quench zone rather than differential pressure in the quench zone. About once per 8-hour shift the quench zone would be cleaned, resulting in a 30°F (17°C) drop in flue gas temperatures due to cooling from the water jacket around the quench nozzles. This allowed a 60-scfm (1.7-m^3/min) reduction in the required flue gas recirculation rate. About 19% of the ash/slag recovered from the SFS was recovered in the dilution/quench zone. This quantity of material is comparable to that from previous tests when the slag screen contained only nine tubes. As discussed in previous reports, reducing the number of tubes in the slag screen was necessary to successfully fire the eastern Kentucky bituminous coal in the SFS. The quantity of material in the quench pot compared to the small number of cleaning episodes suggests that some spontaneous shedding may have been taking place. Downstream of the FGR nozzles, the small quantity of ash observed on the refractory walls was weakly sintered.

Process Air Preheaters

The process air for the CAH tube bank and the RAH panel is heated using air preheater tube bundles located downstream of the CAH. Further heating of the process air entering the RAH panel is achieved electrically. Process air for the CAH tube bank is supplied by the first process air preheater tube bundle. During the September test, process air entering the CAH tube bank was controlled at set points ranging from 1070° to 1135°F (577° to 613°C) for nominal process air flow rates of 95 to 125 scfm (2.7 to 3.5 m^3/min). Process air temperatures at the exits of the other four preheater tube bundles were nominally 1230° to 1310°F (666° to 710°C) for combined flow rates totaling 125 to 180 scfm (3.5 to 5.1 m^3/min).

After 107 hours of coal firing (and 165 hours combined coal and natural gas firing), a leak was discovered in a flex hose in the high-temperature/low-pressure process air system just before the RAH inlet. Because the leak limited process air flow to the RAH, it was decided to terminate the test. The process air leak was relatively small (<20 scfm, <0.6 m^3/min); therefore, it was possible to perform a normal shutdown, controlling the cooldown rate at 100°F/hr (56°C/hr) or less while natural gas was fired. The failed flex hose was replaced with a new flex hose in September and its location and orientation adjusted to reduce its operating temperature and minimize stresses on the hose. In addition, one of two process air flowmeters used to support the CAH tube bank and RAH panel was replaced as a result of its failure to function during a process air line leak check in October.

Process air preheater temperatures are shown as a function of run time in Exhibit 2-8. Although the process air preheater heat-transfer rate degraded with time as ash deposits developed on the tube surfaces, process air temperature and flow rate were adequate to support operation of the CAH tube bank and RAH panel, even after the leak developed in the flex hose near the RAH inlet.

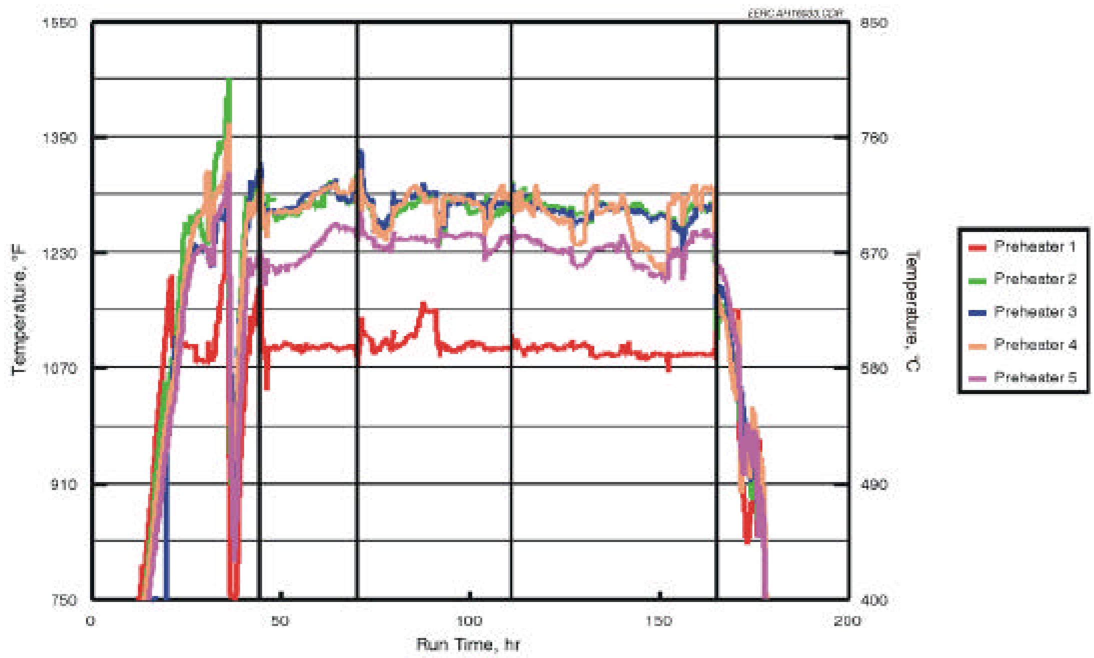

Exhibit 2-8
Process Air Preheater Temperatures Versus Run Time for the September Test, SFS-RH10-0699

Emission Control

During gas- and coal-fired furnace operation in September, baghouse temperatures and temperature profiles were nominal, and the electrical heaters worked well, limiting the potential for condensation on start-up and shutdown. Baghouse temperature ranged from 330° to 390°F (166° to 199°C). Flue gas flow rates were 920 to 1110 scfm (26.1 to 31.4 m^3/min). Actual flue gas flow rates through the baghouse were 1398 to 1814 acfm (39.6 to 51.4 m^3/min).

The 36 bags (total filtration area of 565 ft^2 [52.5 m^2]) used in the baghouse this past quarter were a 22-oz/yd^2 (747 g/m^2) woven glass with a PTFE membrane. The filter face velocities when the Prater Creek bituminous coal was fired were 2.5 to 3.2 ft/min (0.75 to 0.98 m/min). These filter face velocities are low compared to conventional pulse-jet filtration systems typically operating at or near 4 ft/min (1.2 m/min). However, a detailed evaluation of baghouse performance has not been a specific objective within the scope of work to date.

Measured inlet and outlet particulate mass loadings were nominally 0.0624 gr/scf (142.9 mg/Nm^3) and 0.0006 gr/scf (1.3741 mg/Nm^3), respectively, resulting in a particulate collection efficiency of roughly 99% when the Prater Creek bituminous coal was fired in September. These inlet particulate loadings are very similar to those measured when the eastern Kentucky bituminous coal was fired in April and a factor of 2 to 5 lower than measured previously when the Illinois No. 6 bituminous coal was fired. The reason is the smaller theoretical quantity of ash entering the SFS with these Kentucky fuels for a given firing rate, about 35% of that for the Illinois No. 6 fuel. Calculated particulate emissions from the pulse-jet baghouse were 0.0025 lb/MMBtu. This is a reduction by a factor of three in particulate emissions compared to the April test, yet comparable to emission rates previously measured when other coals and lignite (0.0004 to 0.0074 lb/MMBtu) were fired in the SFS. Visual inspection of the outlet filters resulting from September sampling did not indicate the presence of ash agglomerates on the filters, and no evidence of a dust cake was noted. Therefore, the EERC believes that the outlet filters in September (when the Prater Creek fuel was fired) were not affected by acid condensation. Evidence of acid condensation was not found in the clean air plenum of the pulse-jet baghouse and downstream flue gas piping after the September test. Therefore, acid condensation residue from prior Illinois No. 6 coal fired tests had been effectively removed from the SFS prior to the September test.

One sulfur trioxide concentration measurement was made downstream of the pulse-jet baghouse in September. The measurement indicated that when the Prater Creek bituminous coal was fired, the sulfur trioxide concentration at the pulse-jet baghouse outlet was 4 ppm. This value is consistent with the low fuel sulfur content of the fuel and concentrations measured during previous tests firing a similar fuel. During the December test, calcium oxide injection was used to reduce the sulfur trioxide concentration at the baghouse outlet. However, data are not available for discussion here.

In addition to the standard EPA Method 5 sampling completed in September, respirable mass emissions (defined below) were measured at the outlet of the pulse-jet baghouse using a TSI Inc. aerodynamic particle sizer (APS-33). This real-time measurement method measures particle mass in the range of 0.5 to 15 μm. The primary advantages of this system are the high spatial resolution and the short sampling time. In the APS-33, particle-laden air is passed through a thin-walled orifice, with the particles lagging behind the gas because of their higher inertia. This lag allows the determination of the aerodynamic dynamic diameter of a particle by measuring its velocity as it exits from the orifice. To measure the particle velocity, the APS-33 employs a laser beam split in two and refocused onto two rectangular planes a set distance apart in front of the orifice. The light scattered by a particle passing through these beams is collected and focused onto a photomultiplier tube, which emits two pulses separated by the time taken for the particle to cross the distance between the two planes. This time interval is measured electronically and used to calculate the particle's aerodynamic diameter.

Respirable mass is a calculated value defined by the American Council of Governmental and Industrial Hygienists for particles in the aerodynamic size range of 2 to <10 μm. Exhibit 2-9 presents the respirable mass emissions for the September test period. The data are presented on a mg/m^3 basis versus sampling time. The respirable mass emission rate was nominally 0.1 mg/m^3, roughly one to two orders of magnitude higher than the emission rates measured in May (0.016 mg/m^3) and April (0.0024 mg/m^3). Since the total mass emission rate was lower in September than observed in April and May, the higher respirable mass emission rate is somewhat surprising.

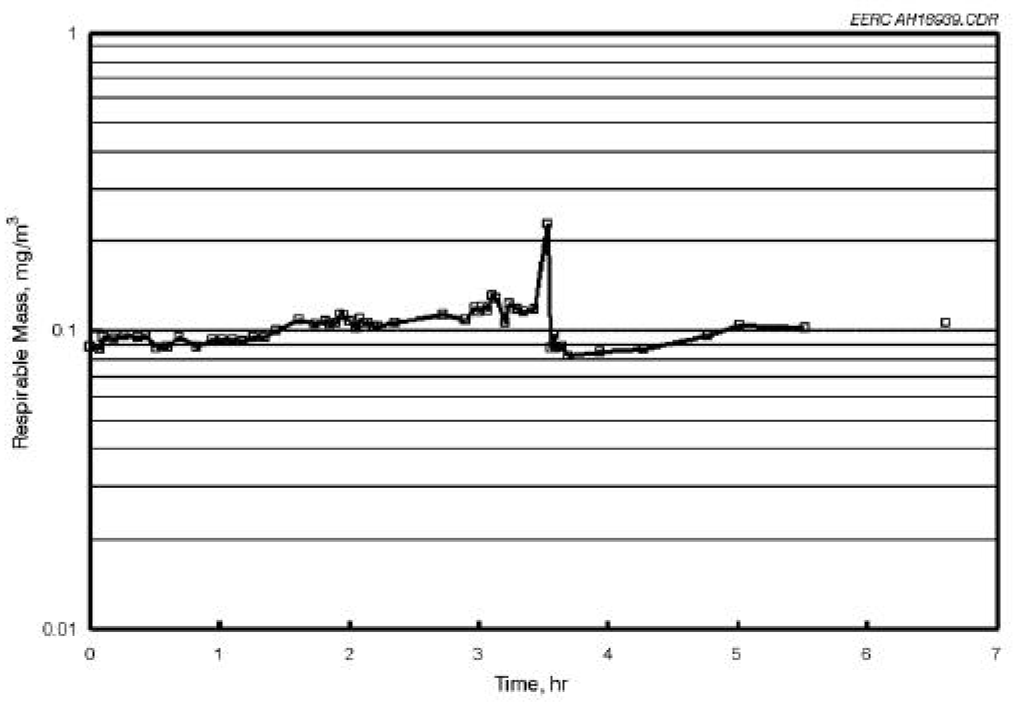

Exhibit 2-9
Respirable Mass Emissions Data for the September Test

Because of the differences observed in the measured particulate emissions from the pulse-jet baghouse, several bags were removed for inspection. The bags were found to be in good condition. Therefore, an explanation other than fuel-specific characteristics for the increase in particulate emissions observed through APS sampling is not available at this time. Particulate sampling during future SFS tests will hopefully provide an explanation for this apparent change in fly ash characteristics baghouse performance.

Particle-size analysis was completed for a composite ash sample collected from the baghouse hopper for the September test. The data show the ash to be 100 wt% <10.5 µm, 80 wt% <6 µm, and 50 wt% <3.5 µm for the Prater Creek coal. These values indicate an ash particle size comparable to that observed when the eastern Kentucky coal was fired in February (100 wt% <10 µm, 80 wt% <5 µm, and 50 wt% <3 µm). The September and February ash particle-size data are significantly smaller than those observed during the April test with the eastern Kentucky coal (100 wt% <25 µm, 80 wt% <10 µm, and 50 wt% <6 µm). The results of the September test suggest that the slag screen configuration has little effect on baghouse ash particle size, while the addition of limestone had a significant effect. While some limestone was fed during the September test, the total amount of limestone fed was only about 0.6% of the total solids fed, compared to 5.0% of the solids fed (during eastern Kentucky coal firing) in the April test. Also, limestone was not injected during the particulate sampling periods completed in September.

Multicyclone sampling data indicated a larger particle size, with nominally 50 wt% <7.5 µm. These multicyclone data are consistent with data observed in April. However, in April limestone addition was used to modify slag chemistry. At this time, there is no obvious explanation for the difference in fly ash particle size data resulting from the baghouse ash sample and the multicyclone measurement in September.

Carbon content was also measured in the baghouse ash to determine combustion efficiency. The carbon content was 0.59 wt% for the Prater Creek coal in September, comparable to the 0.70% carbon in the baghouse for the eastern Kentucky coal fired in April.

Pulse cleaning of the bags was accomplished on-line using a reservoir pulse-air pressure of nominally 60 psig (4.2 bar). The baghouse differential pressure cleaning set point was 5 in. W.C. (9 mm Hg). Once the initial dust cake was formed, the cleaning period was about 2.5 hours. The bags consistently cleaned to a differential pressure of <3 in. W.C. (<6 mm Hg). Previously, the cleaning cycle set point was a baghouse differential pressure of 6 in. W.C. (11 mm Hg); the setpoint was decreased for this run in an attempt to mitigate system upset conditions caused by the change in overall system pressures following baghouse cleaning. While the baghouse differential pressure following cleaning was slightly higher during the September test (<3 in. W.C. or < 6 mm Hg as opposed to <2 in. W.C. or 4 mm Hg), the performance of the baghouse was consistent, and the smaller swing in system pressure drop was a beneficial change in operating protocol.

Table 2-4 shows the average flue gas composition measured during the September test. The data are based on furnace exit measurements made in the slag screen outlet. The CO concentrations in the slag screen were as high as 300 ppm and nominally 80 to 200 ppm during the September test, though typically CO concentrations at the slag screen are virtually nonexistent (<10 ppm). The high CO concentration measured in September indicates that some combustion was taking place in the slag screen. This is supported by the fact that slag screen exit temperatures were often higher than slag screen inlet temperatures. These observations may be the result of the auxiliary burner firing rate, or more likely, the higher main burner firing rate and firing characteristics of the Prater Creek fuel. CO was not observed at the baghouse outlet sampling location unless the slag tap burners were operated at substoichiometric conditions, indicating that any CO observed in the slag screen was oxidized in the dilution/quench zone and CAH section.

Table 2-4
Flue Gas Composition/Emissions for the Prater Creek Coal-Fired Slagging Furnace Test

	Concentration	lb/MMBtu
O_2	2.6%–4.4%	–
CO_2	12.5%–15.3%	–
CO	50–300 ppm	–
NO_x	560–780 ppm	0.94–1.34
SO_2	390–540 ppm	1.2–1.6

NO_x concentrations in the flue gas ranged from 560 to 780 ppm. Total NO_x emissions (reported as nitrogen dioxide) were determined to range from 0.94 to 1.34 lb/MMBtu. NO_x emissions increased as the test progressed, influenced in part by higher average coal feed rates. Also, NO_x emissions were marginally higher for the Prater Creek coal than for the eastern Kentucky fuel fired in April, probably as the result of the higher main burner firing rate. The auxiliary burner firing condition is also believed to have affected the NO_x concentrations and emissions; however, no specific tests have been conducted to document the effect of the auxiliary burner on NO_x emissions.

No attempt at controlling sulfur emissions was made. Calculated maximum theoretical sulfur dioxide emissions were 2.4 to 2.5 lb/hr (1.1 to 1.2 kg/hr) or 1.1 lb/MMBtu for the Prater Creek bituminous coal. These rates are based on the main burner firing rate and the sulfur content and heating value of the fuel. The Prater Creek coal sulfur dioxide emissions, calculated on the basis of measured sulfur dioxide in the flue gas, flue gas flow rate, and the coal firing rate, resulted in values ranging from 1.2 to 1.6 lb/MMBtu. The most likely explanation for the difference in calculated sulfur dioxide emission rates, 1.1 versus 1.2–1.6 lb/MMBtu, is that the composite fuel sample that was analyzed did not adequately represent the sulfur variability documented by the flue gas analyzers.

Testing of the CAH Tube Bank

Exhibits 2-10 through 2-12 summarize CAH tube bank surface and flue gas temperatures, process air temperatures, and process air flow rate data for the September test. Exhibit 2-13 illustrates the location of thermocouples in the CAH tube bank, and Table 2-5 presents a list of thermocouple descriptions.

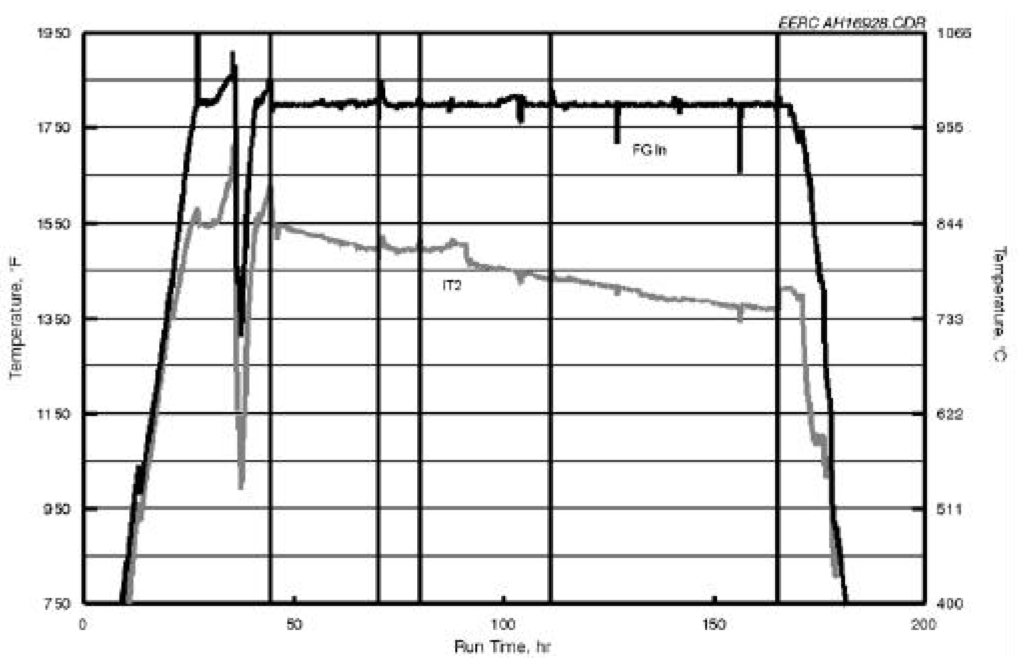

Exhibit 2-10
CAH Tube Surface and Flue Gas Temperatures Versus Run Time for the September Test, SFS-RH10-0699

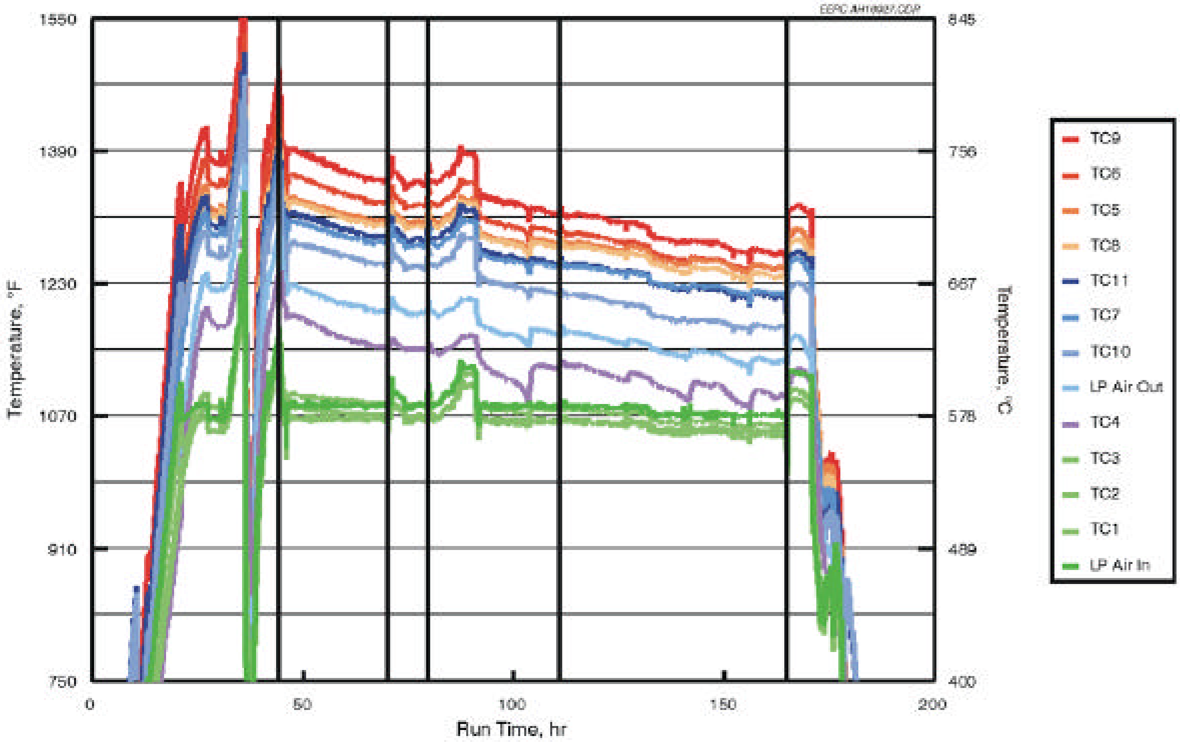

Exhibit 2-11
CAH Process Air Temperatures Versus Run Time for the September Test, SFS-RH10-0699

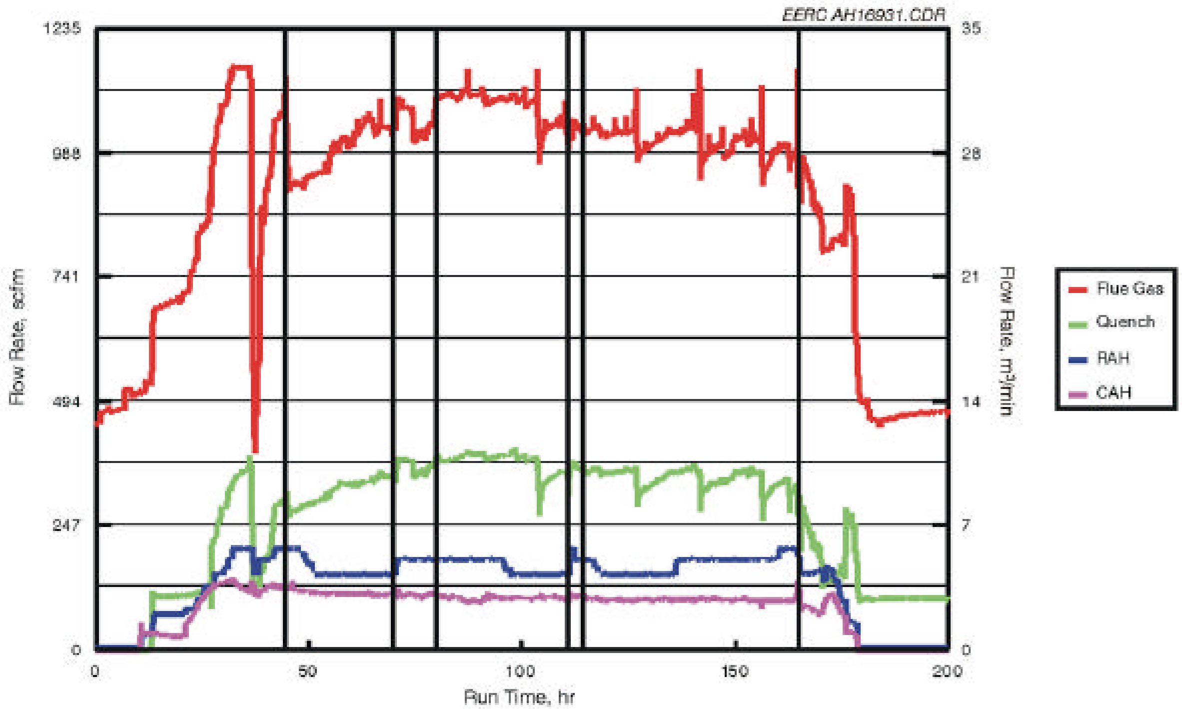

Exhibit 2-12
CAH Process Air, RAH Process Air, Quench Gas, and Flue Gas Flow Rates Versus Run Time for the September Test, SFS-RH10-0699

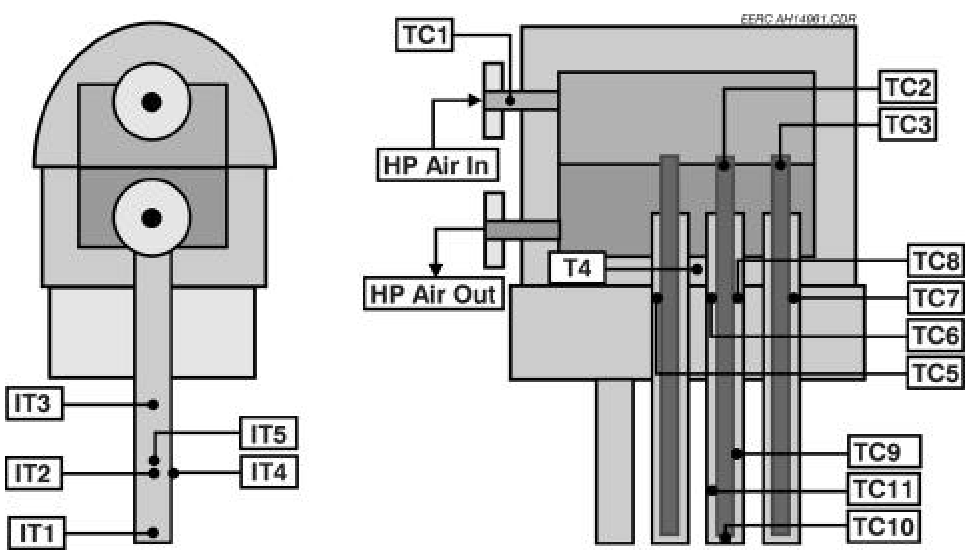

Exhibit 2-13
Thermocouple Locations in the CAH Tube Bank

Prior to an August 1998 test, all of the CAH thermocouples were replaced or repaired in conjunction with the installation of fins on the air-cooled tubes. However, one tube surface thermocouple (CAHIT3) was damaged when the tube bank was installed in the flue gas duct. One additional CAH thermocouple failed during both the August and December 1998 tests, and a fourth thermocouple failed at the beginning of a January 1999 test. Therefore, during the September test, only one of the five surface thermocouples was functioning properly. There are no plans to replace these thermocouples at this time because of the time and expense that would be required. On the basis of a single thermocouple measurement, the clean tube surface temperatures were nominally 1550°F (844°C), with the surface temperature decreasing to 1370°F (744°C) as ash deposits developed and adjustments were made to the process air flow rate.

While natural gas was fired and the tubes were clean, heat recovery from the CAH tube bank was roughly 40,000 Btu/hr (42,200 kJ/hr). The process air flow rate was 120 scfm (3.4 m^3/min). The inlet process air temperature was 1085°F (585°C), outlet process air was 1230°F (666°C), and flue gas was 1800°F (982°C) entering the CAH tube bank. Exhibit 2-14 presents heat recovery in the CAH as a function of run time.

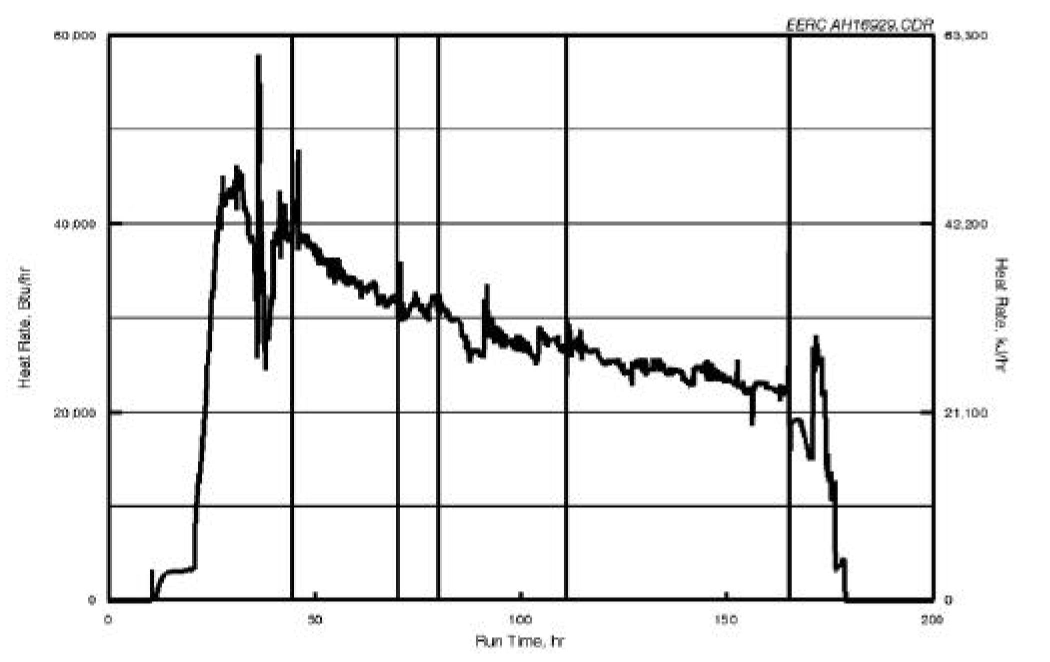

Exhibit 2-14
CAH Heat Recovery Versus Run Time for the September Test, SFS-RH10-0699

When coal firing began, surface temperatures initially decreased at a rate of nominally 5.5°F/hr (3.0°C/hr) over nearly 25 hours as ash deposits developed on the surface of the tubes. After 60 hours of coal firing, the rate of decrease was 2.4°F/hr (1.3°C/hr). This rate continued through the remainder of coal firing. The process air flow rate through the CAH remained relatively constant, nominally 100 scfm (2.8 m^3/min), for the duration of the test. The minimum cooling air flow rate through the CAH tube bank was 94 scfm (2.7 m^3/min). As ash deposits developed on the tube surfaces, heat recovery from the CAH tube bank decreased from roughly 40,000 Btu/hr (42,200°kJ/hr) to 22,500 Btu/hr (23,738 kJ/hr). Heat recovery from the CAH tube bank was stable for the last 8 hours of coal firing.

Table 2-5
Description of CAH Thermocouple Locations[1]

Category	N	Label	Description
Air Inlet	1	CAHTC1	Bulk flow entering the inlet header
	2	CAHTC2	Air entering center tube
	3	CAHTC3	Air entering most downstream tube
Air Outlet	4	CAHTC6	Air leaving center tube
	5	CAHTC7	Air leaving most downstream tube
	6	CAHTC5	Air leaving most upstream tube
	7	CAHTC8	Air leaving side tube
Air in Active	8	CAHTC10	Bottom of center tube
	9	CAHTC11	4 in. up outside annulus, center tube
	1	CAHTC9	8 in. up outside annulus, center tube
Tube Surface	1	CAHIT1	1 in. up center tube, facing upstream (failed)
	1	CAHIT2	5 in. up center tube, facing upstream
	1	CAHIT3	8 in. up center tube, facing upstream (failed)
	1	CAHIT4	5 in. up center tube, facing to side (failed)
	1	CAHIT5	5 in. up center tube, facing downstream
Header Shell	1	CAHTC4	Next to shell on outside, between return air

[1] Thermocouple locations are illustrated in Exhibit 2-13.

These data continue to support the conclusion that the addition of the fins to the air-cooled tubes improves heat recovery during the coal-fired test periods. The fins appear to reduce the rate of heat-transfer degradation as ash deposits developed and help to maintain a higher heat-transfer rate once the deposits have formed. However, no improvement in heat recovery was observed during the initial natural gas-fired periods with clean tube surfaces.

EERC personnel did not clean the CAH tube bank during the September test, and ash deposits were not characterized because of the limestone injection that occurred for several hours at the beginning of the test. The deposits that formed were limited to the leading and trailing edges of the tubes. Exhibit 2-15 presents a photograph of ash deposits on the surface of the tubes following the September test. The photograph shows three of the five uncooled tubes as well as two of the seven air-cooled finned tubes. Leading- and trailing-edge deposits are visible. However, the ash deposit mass appears limited and inconsistent with bare metal surfaces visible on areas of both uncooled and cooled tubes. Most of the leading edge deposit is missing from the first two uncooled tubes, having either sloughed off during the test or fallen off upon cooldown or removal of the tube bank from the duct.

Exhibit 2-15
Photograph of Ash Deposits on the CAH tubes Following the September Test Firing Prater Creek Bituminous Coal

Deposit strength is a function of ash chemistry, particle size, and temperature history. The deposits on the air-cooled finned tubes generally remained intact when the CAH tube bank was removed from the duct. Although this may be an indication of moderate deposit strength, the observation is more likely indicative of the small deposit mass. The total weight of the deposits collected from the CAH tubes and duct was 15.5 lb (7.0 kg). The total weight of the deposits collected from the CAH tubes was 2.5 lb (1.1 kg). On a mass per unit time basis, the ash deposition rate on the CAH would be 0.02 lb/hr (10.6 g/hr) of coal firing. Incorporating the surface area of the tube bank (6.28 ft^2 or 0.58 m^2) results in a value of 0.004 lb/hr-ft^2 (18.3 g/ hr-m^2). On a coal-firing-rate basis, the CAH ash deposition rate would be 0.01 lb/MMBtu (5.9 g/10^6 kJ). These values are consistent with those reported for the eastern Kentucky coal fired in February as well as the ash content and heating value of the fuel compared to other fuels fired in the SFS.

Testing of the RAH Panel

Initial shakedown and testing of the RAH panel took place in December 1997. Testing of the RAH panel continued in September following its reassembly in January 1999 as well as this past quarter following the replacement of the RAH ceramic tiles in early December 1999. The balance of the RAH discussion will focus on the September 1999 data and RAH tile replacement in December. The primary purpose of the September (SFS-RH10-0699) test was to evaluate the RAH panel performance relative to heat transfer, tile and tube temperatures, and process air temperatures and flow rates. In addition, a critical aspect of RAH panel performance is the ability of the ceramic tiles to withstand the slag attack and thermal cycling conditions in the slagging furnace. Therefore, further exposure of the ceramic tiles to slagging furnace conditions was also important. Generally, the performance of the RAH panel in September was nominal, with no significant process or material problems observed.

The RAH panel ceramic tiles were thoroughly inspected upon initial installation in January 1999 and following the September test period. The initial inspection revealed the presence of minor cracks in two of the five ceramic tiles. Cracks were not visible in either the top or bottom support blocks. Exhibit 2-16 is a photograph of the new ceramic tiles installed on the RAH panel inside the slagging furnace prior to the January 1999 test. The cracks visible at the time were hairline cracks in the large upper and lower tiles. The large upper tile had five visible cracks originating from the left edge and one crack originating from the top edge. Cracks originating from the left edge were about 0.75 in. (1.9 cm) in length and are not visible in the photograph. The vertical crack is visible in the photograph due to the application of a blue dye. In addition, rough surface pitting of the tile is evident at the end of the vertical crack in the upper center of the tile. The large lower tile had one crack originating on the left edge and a few rough surface pits along the right edge near the middle of the tile. Neither the crack nor the surface pits in the large lower tile are visible in the photograph.

Exhibit 2-16
Photograph of New Ceramic Tiles Installed on the RAH Panel Inside of the Slagging Furnace in January 1999

Exhibit 2-17 presents a photograph of the furnace interior after the September test. The photograph illustrates the good condition of the high-density furnace refractory as well as the darkening of the refractory with exposure to slag. With each period of coal firing, the high-density furnace refractory gets darker. The high-density refractory immediately below the RAH panel is showing signs of deterioration as a result of slag dripping off the bottom RAH support brick onto the refractory. The condition of the RAH ceramic tiles is not clear in this photograph. However, the broken corners on the lower edge of the small upper tile are evident.

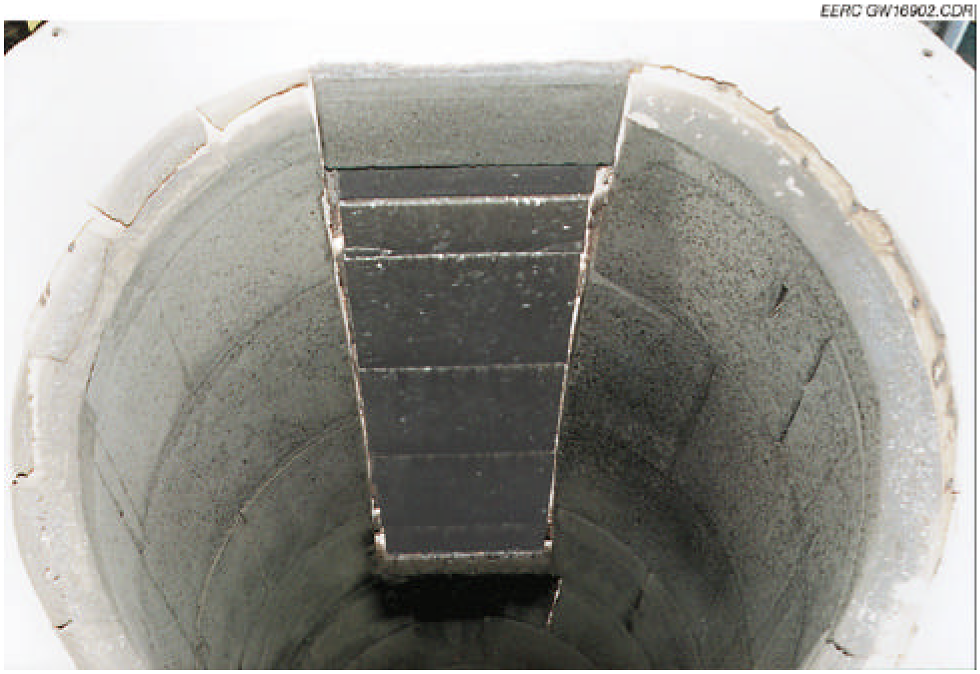

Exhibit 2-17
Photograph of the RAH Panel Inside of the Slagging Furnace Following the September Test

A residual slag layer on the surface of the RAH ceramic tiles following coal firing in January 1999 caused the tile surface to darken. No additional tile color change is evident following the September test. Although not obvious in the photos, the slag layer on the tiles is thin and appears to be uniform, with no evidence of any extensive slag buildup. While slag is present in the seams between the tiles, there is no evidence of any fusion between adjacent tiles except by the frozen slag. Therefore, the 4-hour period of natural gas firing at full load prior to SFS cooldown appears to be adequate to prevent buildup of excess slag on the surface of the tiles or in the seams between tiles. Also, any quantity of slag present in the seams between tiles appears to crack as a result of cooldown and tile movement.

Exhibit 2-18 illustrates the visible cracks found in the RAH tiles following the September test. Overall, the condition of the tiles is deteriorating with each test. The small and large upper tiles appear to exhibit the most severe cracking to date. Following completion of the September test, only the small lower tile was observed to be free of cracks. However, the small lower tile is showing the greatest degree of erosion/corrosion. This is believed to result from the combination of its higher surface temperature and the greater quantity of slag flowing over its surface during SFS tests relative to the other tiles. The surface temperature of the small lower tiles, although not measured, is believed to be higher than the three larger tiles, because the backside of this tile is insulated and is not directly cooled by the heat-transfer surfaces. The greatest quantity of slag also flows over this tile because of its location below the other tiles.

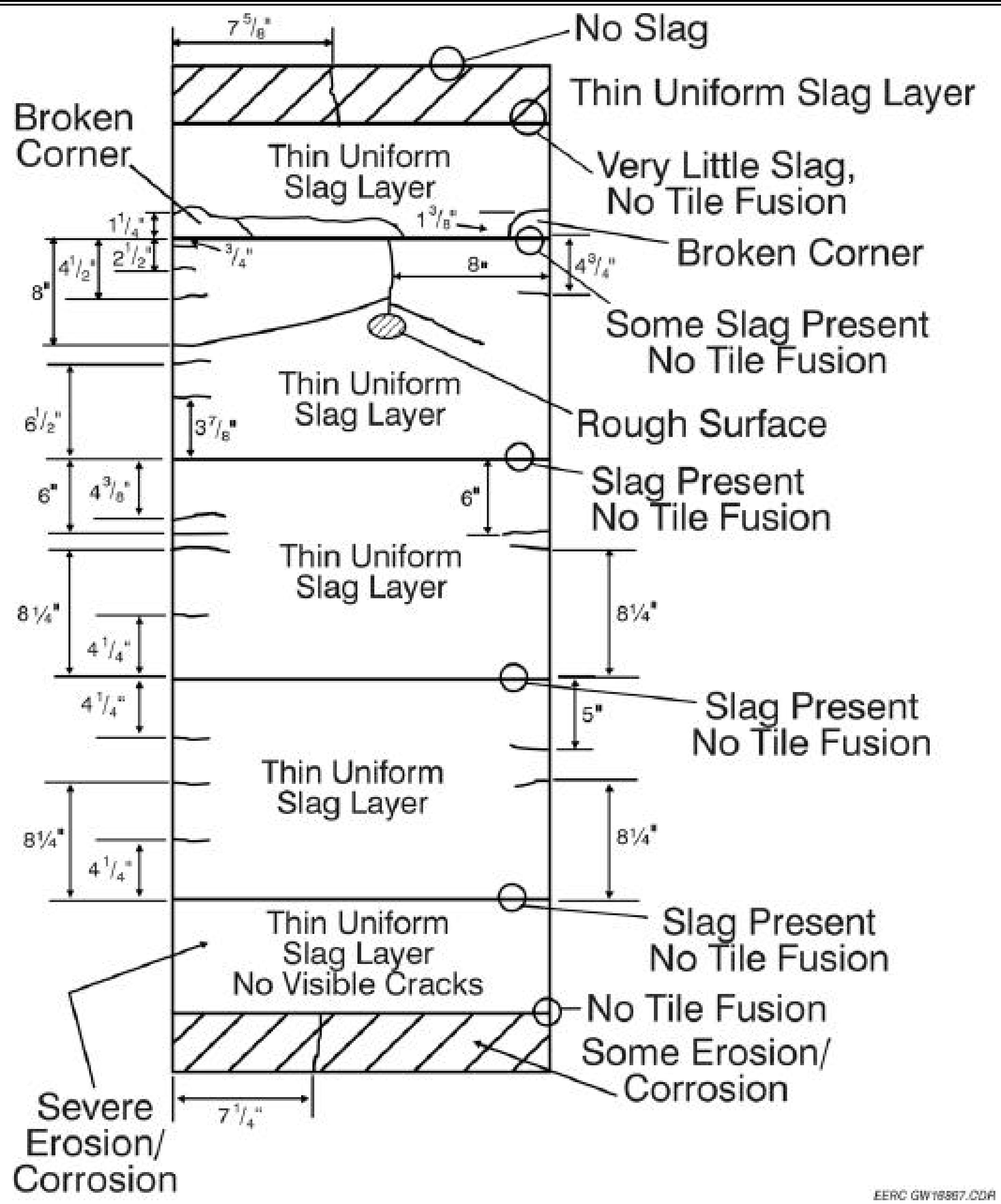

Exhibit 2-18
Illustration of Cracks Found in the Ceramic Tiles/Bricks of the RAH Panel Following the September Test

Heatup/cooldown cycles are believed to be the primary cause of RAH panel ceramic tile/brick crack propagation, with slag contributing to erosion/corrosion of surfaces and imparting stresses on the ceramic tiles as it finds its way into seams between tiles. Exhibit 2-19 presents a photograph of the small upper RAH tile following the September test. The photograph shows the two broken lower corners. However, both pieces are secured in place as a result of slag fusion. Exhibit 2-20 is a photograph of the small lower RAH tile, where the flow of slag has caused severe erosion/corrosion of the tile surface. Both photographs illustrate the small quantity of slag found in the seams between the tiles.

Exhibit 2-19
Photograph of the RAH Small Upper Tile Following the September Test

Exhibit 2-20
Photograph of the RAH Small Lower Tile Following the September Test

Exhibits 2-21 through 2-23 summarize the RAH ceramic tile temperatures, tube surface temperatures, and process air temperatures for the September test (SFS-RH10-0699). The process air flow rate data for the RAH panel were summarized in Exhibit 2-12. Exhibit 2-24 illustrates the location of thermocouples in the RAH panel, and Table 2-6 describes the RAH thermocouples. The indicated ceramic tile surface temperatures (cavity-side) ranged from nominally 1975° to 2110°F (1080° to 1155°C), based on measurements made at the center of each of the three large tiles once the SFS had stabilized thermally (Run Hours 50 through 165). Temperatures as high as 2160°F (1183°C) were measured by TC 25, but since this thermocouple failed at Run Hour 85, those readings are suspect. Higher tile surface temperatures (furnace-side), 2470° to 2675°F (1355° to 1469°C), were measured near the center of the large middle tile (TC 23). Tile surface temperatures during the September test were somewhat higher than the temperatures observed during the RAH coal-fired tests in April or May because of the higher furnace firing rate and resulting furnace gas temperatures.

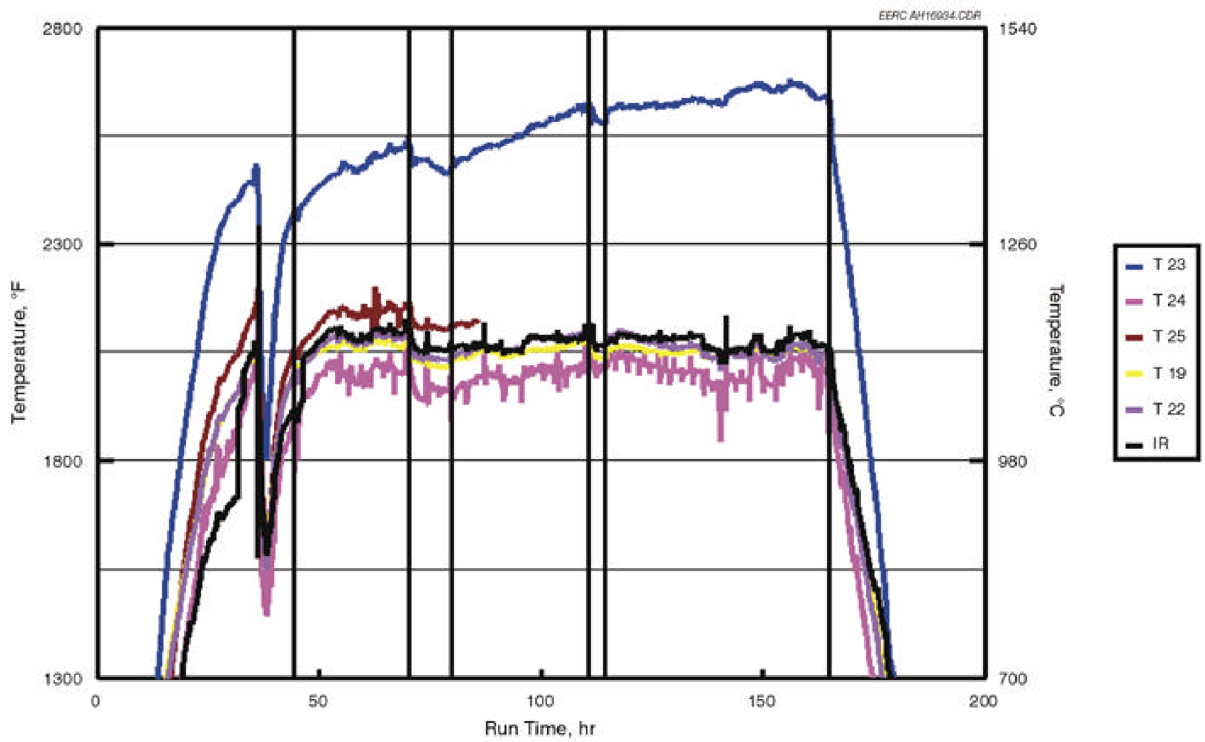

Exhibit 2-21
RAH Ceramic Tile Temperatures Versus Run Time for the September Test, SFS-RH10-0699

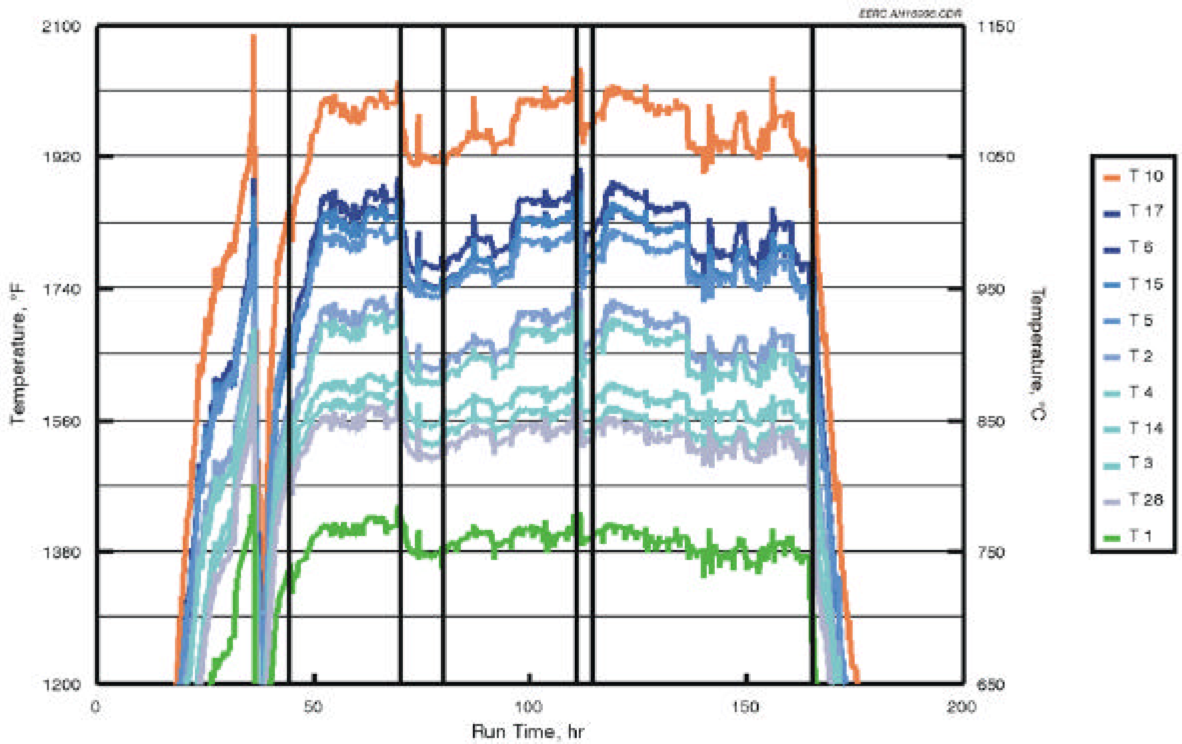

Exhibit 2-22
RAH Tube Surface Temperatures Versus Run Time for the September Test, SFS-RH10-0699

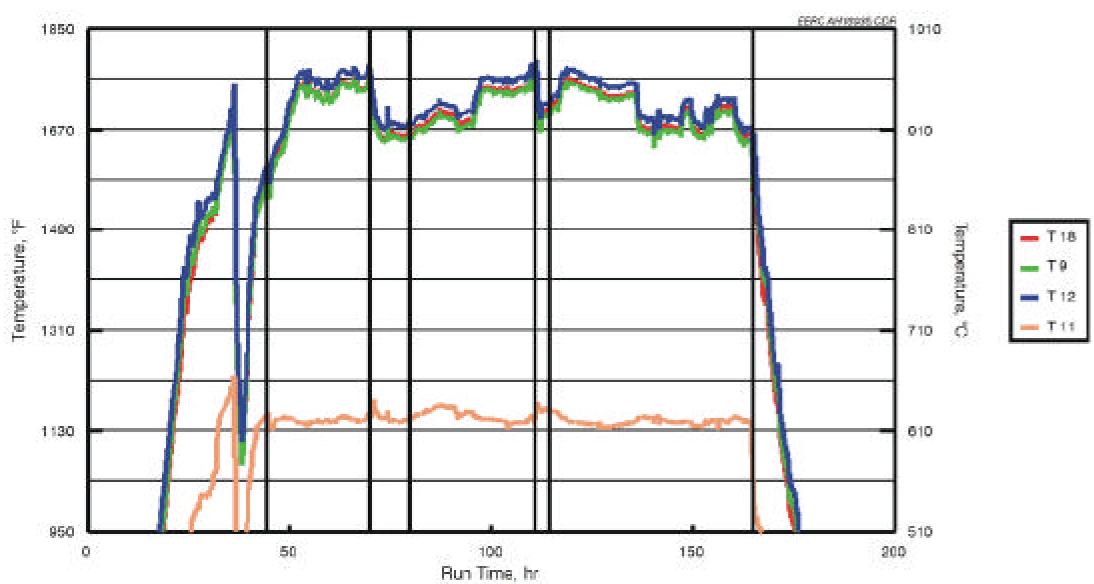

Exhibit 2-23
RAH Process Air Temperatures Versus Run Time for the September Test, SFS-RH10-0699

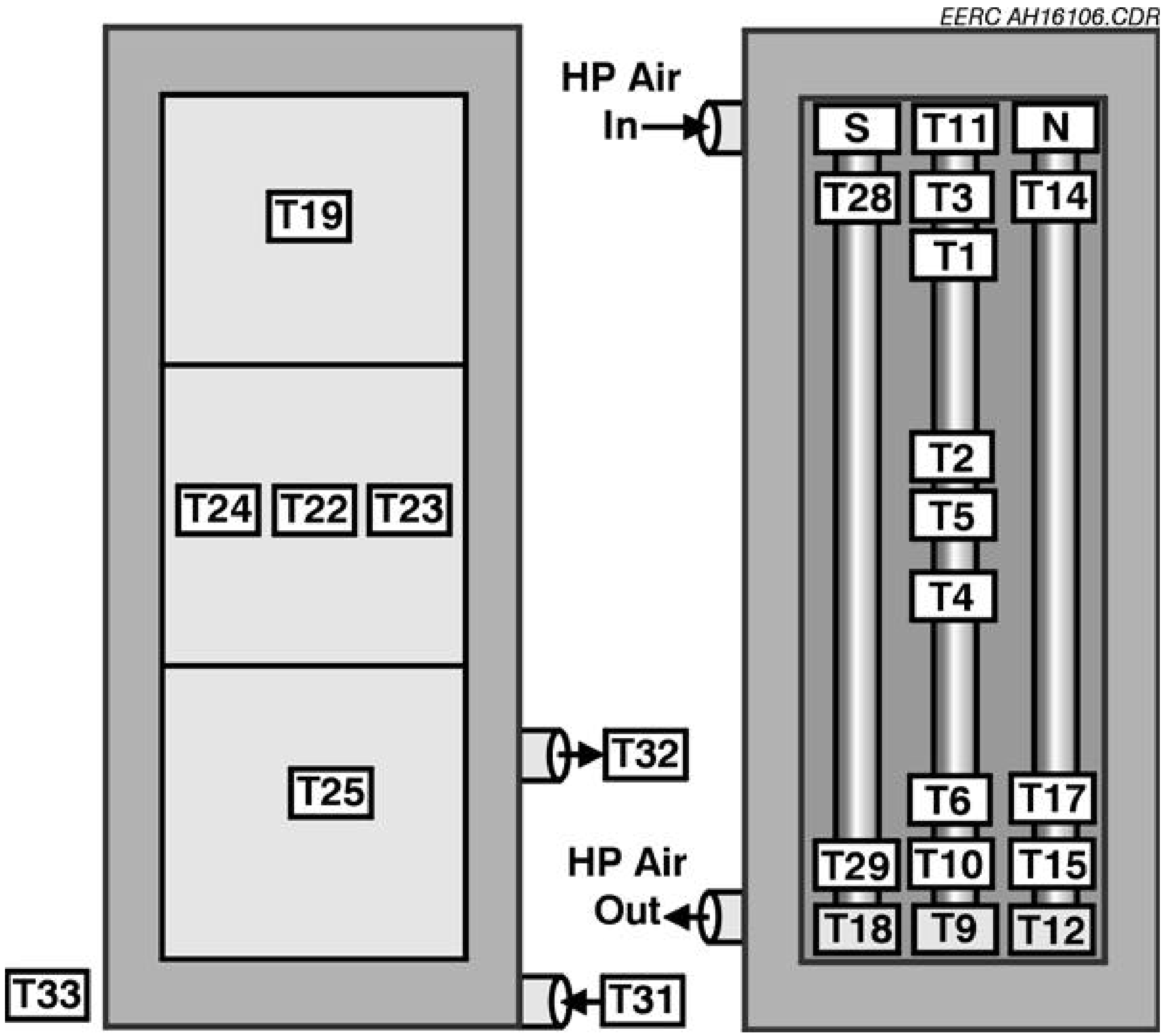

Exhibit 2-24
Thermocouple Locations in the RAH Panel

Table 2-6
Description of RAH Panel Thermocouple Locations[1]

Category	No.	Label	Description
Air Inlet	1	HP Air	Provided by the EERC, in pipe before inlet
	2	RAHT11	Air entering RAH through center tube
Air Outlet	3	RAHT18	Air leaving left (south) tube
	4	RAHT9	Air leaving middle tube
	5	RAHT12	Air leaving right (north) tube
MA Tube	6	RAHT1	Top of middle tube facing cold side
	7	RAHT2	Middle of middle tube facing other tube
	8	RAHT3	Top of middle tube facing toward furnace
	9	RAHT4	Middle of middle tube facing cold side
	10	RAHT5	Middle of middle tube facing toward furnace
	11	RAHT6	Bottom of middle tube facing cold side
	12	RAHT7	Removed
	13	RAHT8	Removed
	14	RAHT10	Bottom of the middle tube facing toward
	15	RAHT13	Removed
	16	RAHT14	Top of north tube facing toward furnace
	17	RAHT15	Bottom of north tube facing toward furnace
	18	RAHT16	Removed
	19	RAHT17	Bottom of north tube facing toward side wall
	20	RAHT28	Top of south tube facing toward furnace
	21	RAHT29	Bottom of south tube facing toward furnace
Inner Surface of Monofrax bricks	22	RAHT19	Top tile, center
	23	RAHT20	Removed
	24	RAHT21	Removed
	25	RAHT22	Middle tile, center
	26	RAHT23	Middle tile, right center hot-side surface
	27	RAHT24	Middle tile, left side rail
	28	RAHT27	Removed
	29	RAHT25	Lower tile, center
	30	RAHT26	Removed

[1] Thermocouple locations are illustrated in Exhibit 2-24.

RAH process air flow rates during the September test were controlled at 150, 180, and 200 scfm (4.2, 5.1, and 5.7 m^3/min), with most of the operational time split between 150 and 180 scfm (4.2 and 5.1 m^3/min). Changes in process air flow rates had a definite effect on indicated tile surface temperatures. As flow rates were reduced, tile surface temperature increased. Subsequently, when process air flow rates were increased, tile surface temperatures decreased. This effect is most evident for flow rate changes at Run Hours 96, 135, and 160.

RAH tube surface temperatures ranged from nominally 1365°to 2010°F (741° to 1099°C). The low end of the temperature range represents the back side of the tube surfaces near the process air inlet, with the high end of the temperature range representing the front side of the tube surfaces near the process air outlet. Changes in process air flow rates had noticeable effects on all tube surface temperatures. Tube surface temperature step changes were most noticeable for surface temperature measurements near the process air exit and on the front side of the tubes. Tube surface temperatures in September were comparable to those for all previous bituminous coal-fired tests.

Process air inlet temperatures ranged from 1136° to 1177°F (613° to 636°C) during the coal-fired operational period. Outlet process air temperatures ranged from nominally 1650° to 1775°F (899° to 968°C). The effect of process air flow rate can be seen in the process air outlet temperature data. As process air flow rate decreases, exit temperature increases, as expected. These flow rate changes are noted at Run Hours 96, 135, and 160.

Heat recovery data from the RAH panel are presented in Exhibit 2-25 for the September test. At process air flow rates of 150, 180, and 200 scfm (4.2, 5.1, and 5.7 m^3/min), the heat recovered from the RAH panel was 110,000 to 117,350 Btu/hr (116,050 to 123,804 kJ/hr), 118,370 to 129,080 Btu/hr (124,880 to 136,179 kJ/hr), and 127,370 to 132,650 Btu/hr (134,375 to 139,946 kJ/hr), respectively. The heat recovery ranges are a function of minor adjustments to the coal feed rate and combustion air flow rates. The main burner firing rate was nominally 2.1 to 2.3 MMBtu/hr (2.2 to 2.4 × 10^6 kJ/hr).

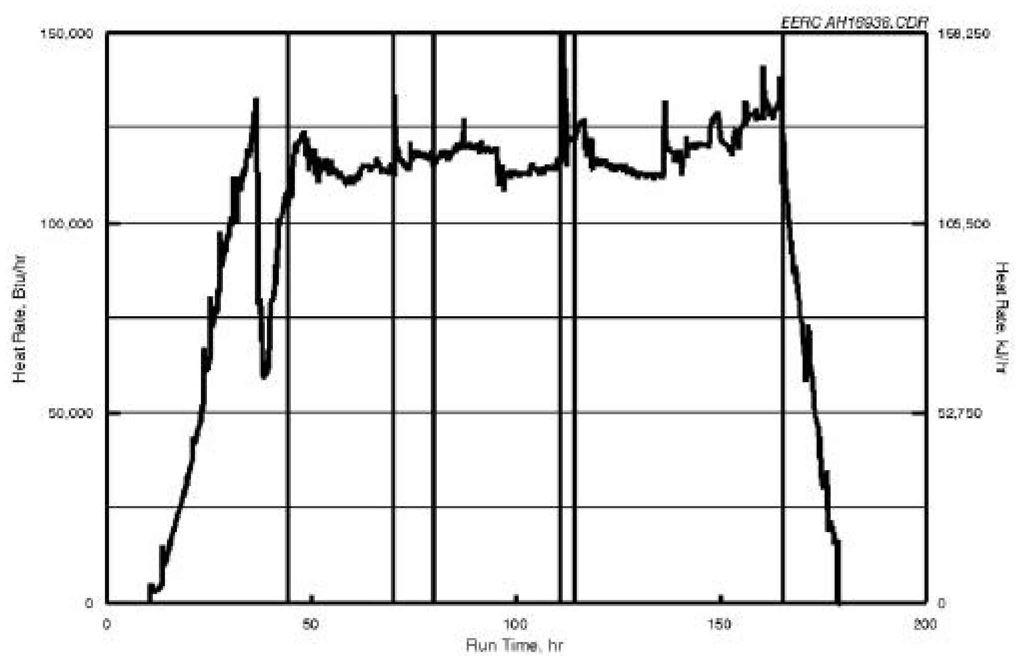

Exhibit 2-25
RAH Heat Recovery Versus Run Time for the September Test, SFS-RH10-0699

Exhibit 2-26 summarizes RAH heat recovery data at process air flow rates of 180 and 200 scfm (5.1 and 5.7 m^3/min) for bituminous coal-fired tests completed in 1998 through September 1999. A comparison of the RAH panel data for the September (RH10) Prater Creek bituminous coal-fired test and the April (RH8) test firing a similar fuel shows a definite increase in the heat recovery rate of 3% to 6%. In April, the heat recovery rate in the RAH panel was 115,385 to 125,000 Btu/hr (121,731 to 131,875 kJ/hr). One reason for the higher RAH heat recovery in September is believed to be the higher average coal firing rate (4%–5%) and resulting furnace gas temperatures (110°–120°F/61°–67°C). However, data generated in September (RH10) and February (RH7) show that the February (RH7) RAH heat recovery rate was somewhat higher than the September (RH10) data, even though the coal firing rate and furnace gas temperature differentials were similar to the comparison with April (RH7) data. Therefore, coal firing rate and furnace gas temperatures are not the only controlling factors influencing heat transfer to the RAH panel.

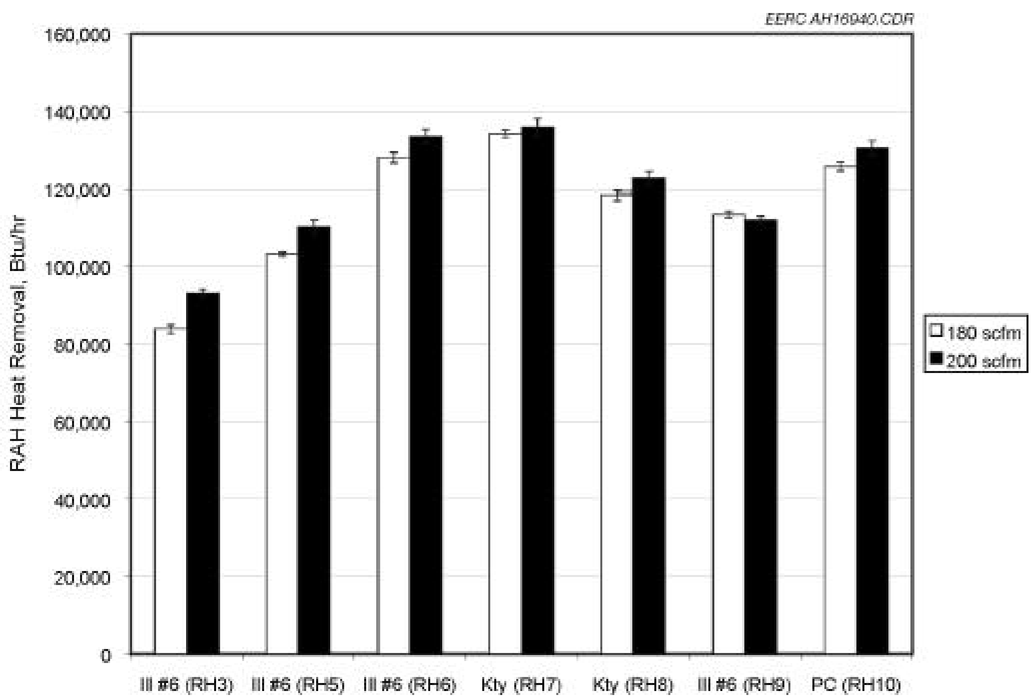

Exhibit 2-26
RAH Heat Recovery for Bituminous Coal-Fired Tests Completed in 1998 and 1999

A comparison of the RAH panel data for the May and January 1999 tests firing Illinois No. 6 bituminous coal shows that the heat recovery rate in May was lower by 13% to 20%. However, the May heat recovery rates are comparable to those for the Illinois No. 6 bituminous coal-fired test in August 1998, where heat recovery rates in the RAH panel were <120,000 Btu/hr (<126,600 kJ/hr) for a process air flow rate of 180 scfm (5.1 m^3/min). A similar comparison to data generated in February 1998 shows that the RAH heat recovery rate in May 1999 was 25% higher at comparable SFS operating conditions.

The reasons for the variations in heat recovery rate are twofold. First, for tests up to and including the August 1998 tests, a small radiant air heater was also present in the furnace. This removed heat from the furnace and reduced the heat recovery rate by the RAH. After the August test, the small radiant air heater was removed from the system. Therefore, direct comparisons of RAH heat recovery are only valid for tests completed in the past 12 months (RH6, RH7, RH8, RH9, and RH10). A second reason for heat recovery variability in the RAH can be seen in comparisons of RH6 and RH9 (firing Illinois No. 6 coal), and RH7 and RH8 (firing eastern Kentucky coal). In both cases, heat recovery by the RAH was lower for the second tests for each coal type. These data indicate that the heat recovery rate for the RAH panel is decreasing with each week of operation.

The reason for this reduction in heat recovery with time is not well understood, but EERC personnel believe that several factors are influencing the reduction. One possibility is a potential change in heat flux to the RAH ceramic tiles resulting in a decrease in the heat transfer to the radiation cavity. The flame-side surface of the RAH ceramic tiles did darken as a result of slag coating and absorption during the January 1999 test. However, it is not clear what the effect would be on radiant heat absorption or emission, or thermal conductivity. Also, no additional color changes were noted following subsequent test periods. Another possibility is that the changing heat flow may be related to ceramic tile deterioration with each week of coal-fired furnace operation as a result of slag erosion/corrosion. Erosion/corrosion of the ceramic tiles may be affecting their heat-transfer properties.

Another potential contributing factor to the decreasing heat flow may be the high-density furnace refractory color change observed with each week of operation. As the high-density refractory has darkened with each week of operation, it is possible that the reflectivity or emissivity characteristics of the furnace liner have changed, resulting in a decrease in radiation to the RAH panel. Further testing and data review will be necessary to determine if the observed decrease in RAH panel heat recovery rate continues with each week of testing or if an alternate explanation can be identified.

As previously stated, the ceramic tiles were removed from the RAH panel in November 1999 in preparation for the installation of new tiles in December. The RAH panel ceramic tiles were thoroughly inspected upon installation. Exhibit 2-27 illustrates the cracks found in the tiles/bricks, and Exhibit 2-6 is a photograph of the furnace interior after the tiles were installed. The three new fusion-cast alumina Monofrax M tiles (small upper tile, large lower tile, and small lower tile) had minor cracks. In addition, the small lower tile had one significant crack that extended from the top to the bottom edge. None of these cracks are visible in the photograph.

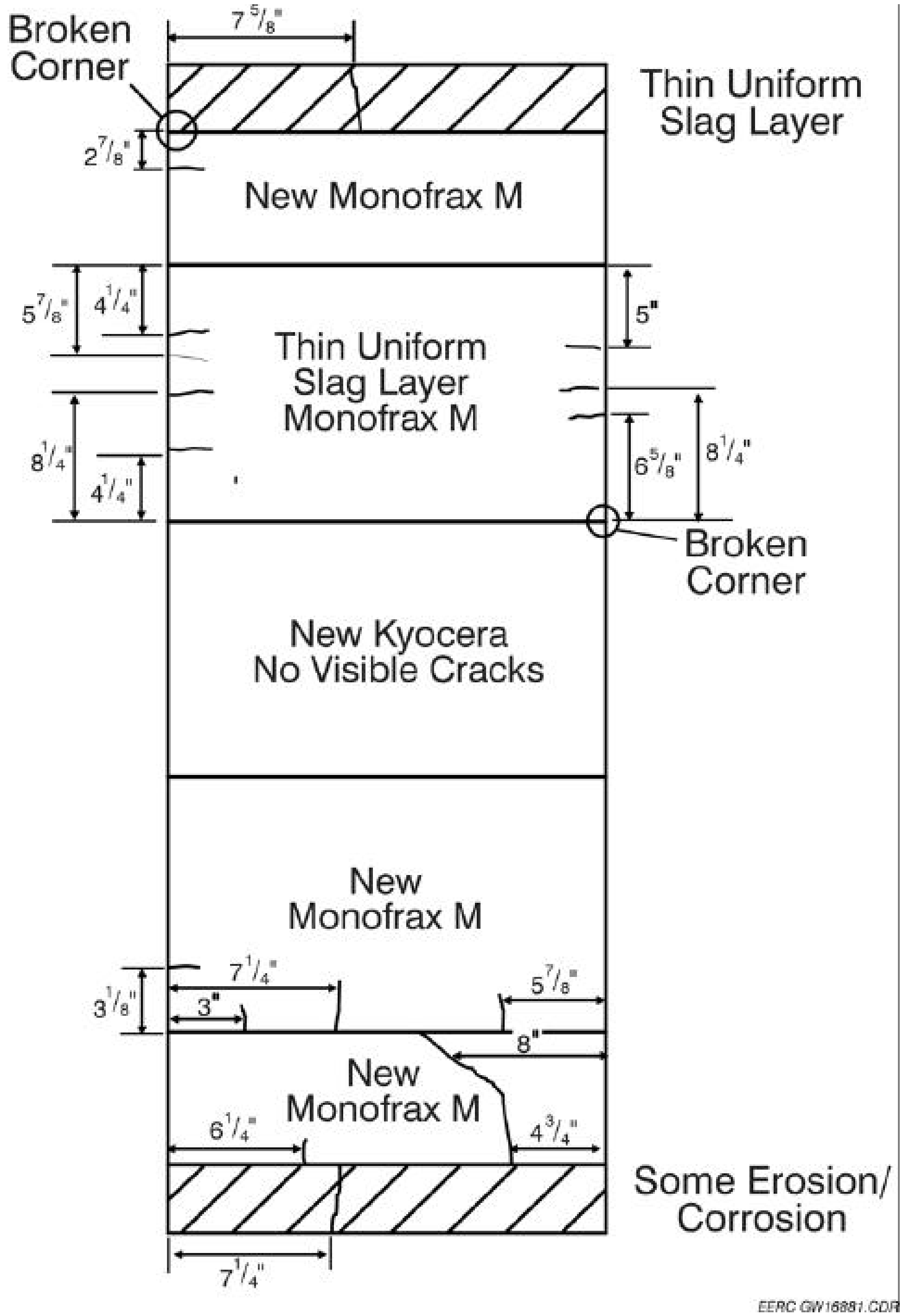

Exhibit 2-27
Illustration of Cracks Found in the New and Used Ceramic Tiles/Bricks Installed in the RAH Panel Prior to the December Test, SFS-RH11-0799

Only one new sintered chromia–alumina Kyocera tile was installed because a second tile had four broken corners as well as a large number of small cracks extending from each edge. The damage to the second Kyocera tile occurred as a function of curing and machining prior to shipment to the EERC. The new Kyocera tile was installed in the center tile position and did not have any visible cracks. However, the upper right corner of the Kyocera tile was broken as a result of some machining that was performed at the EERC prior to its installation. Because only one large new Monofrax M tile was available, it was necessary to reuse one of the Monofrax M tiles originally installed in January 1999 as a replacement for the second Kyocera tile. This large tile had been in the lower position on the panel and is now in the upper position, as seen in the Exhibit 2-6 photograph. Five cracks are evident in this tile, four extending from the left edge and three extending from the right edge. The top and bottom support bricks were reused, with each having one vertical crack extending through the face.

Table 2-7 summarizes operating time for the SFS, CAH tube bank, and RAH panel. Through December 1999, the RAH panel has been exposed to a range of furnace-firing conditions for a total of 2288 hours. Natural gas firing represents 1187 hours (including heatup, cooldown, and refractory curing), and coal/lignite firing represents 1101°hours. In addition, the RAH panel has been exposed to fourteen heating and cooling cycles. The RAH ceramic tiles that were installed in January 1999 were exposed to six heating and cooling cycles and 988 hours of slagging furnace operation: 473 hours of natural gas firing (including heatup and cooldown) and 515 hours of coal firing. With the exception of the one Monofrax M tile that was reused, the RAH ceramic tiles that were installed in December 1999 have been exposed to one heating and cooling cycle and 295 hours of slagging furnace operation: 94 hours of natural gas firing (including heatup and cooldown) and 201 hours of coal firing. The longest continuous coal-fired period was 184 hours, completed in April 1999. The next SFS operating period, a 200-hour test firing a Powder River Basin subbituminous coal, is tentatively scheduled for February or March 2000.

Table 2-7
Summary of Operating Hours for the SFS, CAH Tube Bank, and RAH Panel Through December 1999

	Natural Gas Firing, hr	Coal/Lignite Firing, hr	Total Operation, hr
Slagging Furnace System	1686	1181	2867
CAH Tube Bank	1371	1148	2519
RAH Panel	1187	1101	2288

Task 2.2.5.2 – Laboratory- and Bench-Scale Activities

Alloy Corrosion Testing

In previous, separately funded, work performed at the EERC, a temperature window was identified in the thermochemical behavior of the products of coal combustion in which it is believed the products may be much less corrosive toward structural materials. The window ranges from a low temperature of approximately 2000°F (1090°C) to an upper, fuel-dependent, temperature of approximately 2300°F (1260°C). The window is believed to exist, because above the lower limit, condensed sulfates are not stable in the ash (Hurley and Benson, 1995). Below the upper limit, many coal ashes have very high viscosities, so mass transfer of corrodents to the structural materials is relatively slow.

To help determine whether or not this low-corrosion temperature window exists, laboratory corrosion tests of the heat exchanger alloy are being performed. During this quarter, five coupons of Alloy MA-754 were cut into 1- × 5/8-in. (2.5-× 1.6-cm) coupons for the corrosion testing. The testing was carried out with an enclosed horizontal tube furnace equipped with inlet and outlet ports. The coupons were first subjected to 100 hours of oxidation at 2100°F (1150°C). This temperature was chosen because it is the approximate temperature of the alloy in the RAH when 2000°F (1090°C) pressurized air is being produced – the highest temperature so far tested (see the July–September 1998 quarterly technical progress report). The coupons were then covered with a layer of powdered Illinois No. 6 slag and heated in the presence of a simulated combustion gas for 500 hours at 2100°F (1150°C). The gas was composed of 13% CO_2, 4% O_2, 900 ppm SO_2, 9% water, balance N_2 at a flow rate of 0.5 ft^3/hr (0.2 L/min.). Coupons were removed after 100, 200, 350, and 500 hours of exposure for mass loss calculations. A second coupon exposed for 500 hours was mounted in epoxy with the corrosion and ash layers intact, and cross-sectioned for SEM analysis.

Corrosion rates were calculated by mass loss according to ASTM Procedure G1-88. To perform the procedure, the coupons were sonically cleaned in successive chemical baths to remove corrosion products. The coupons were then weighed after drying, and mass loss from the original oxidized coupon was determined. From the mass loss, a corrosion rate can then be calculated. A plot of the cumulative corrosion is shown in Exhibit 2-28. As the figure indicates, the cumulative corrosion after 500 hours was found to be approximately 0.35 mils (9 µm), which suggests a maximum corrosion rate of 6.2 mils/year (157 µm/year). The weighing error for these samples should be no more than approximately 2% relative.

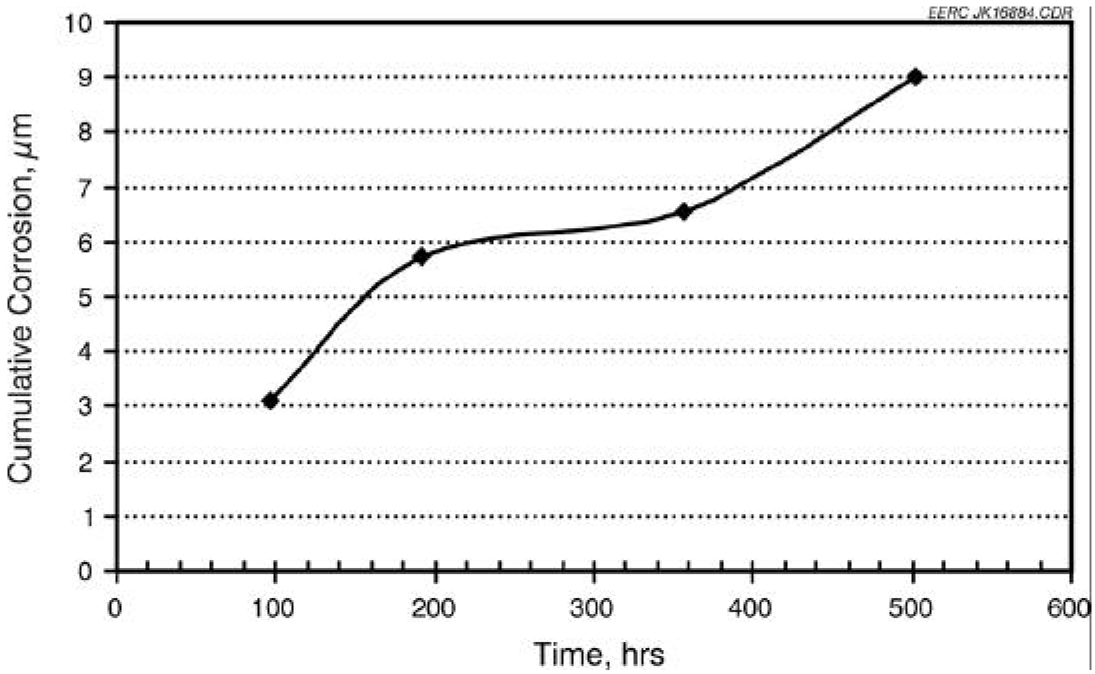

Exhibit 2-28
Cumulative Corrosion of Alloy MA-754 at 2100°F (1150°C)

The coupon tested for 500 hours that was examined by SEM had a chromium oxide layer at the alloy–ash interface that was approximately 0.08 to 0.3 mils (2–8 µm) thick across the entire surface. The depth of oxidation penetration was over 2 mils (50 µm). A SEM micrograph is shown in Exhibit 2-29. Sulfur was not detected in the oxidation zones or in the alloy. The early formation of a few small pits was observed, which extended to a depth of 0.4 mils (10 µm). The Illinois No. 6 slag was well sintered, but did not stick to the alloy.

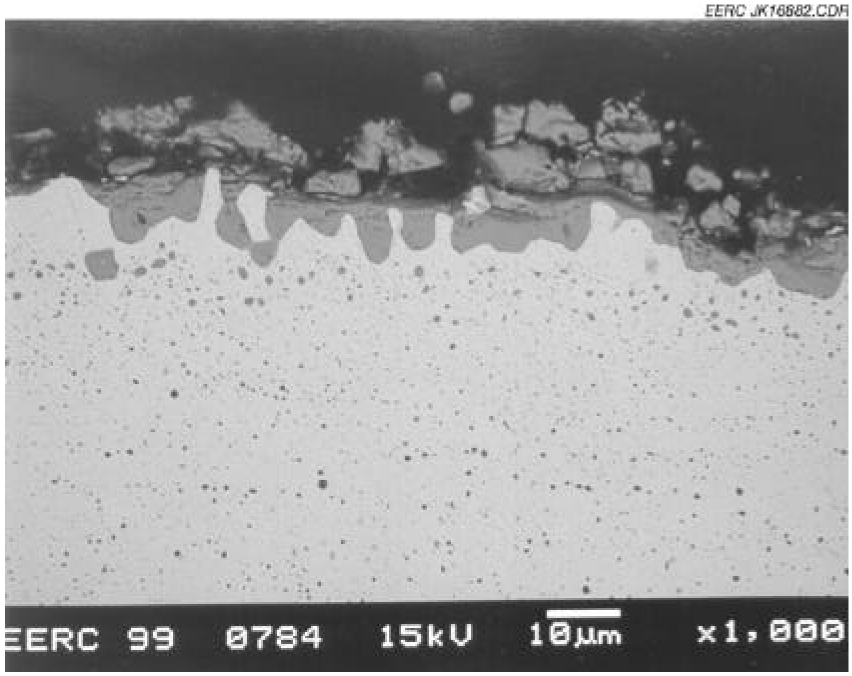

Exhibit 2-29
SEM Micrograph of Alloy MA-754 Showing Oxide Layer

Exhibit 2-30 shows x-ray maps generated during SEM examination. The chromium oxide layer can be clearly seen. Iron detected at the surface of the oxide layer originated in the slag. Niobium was well dispersed throughout the alloy, in contrast to other alloys that we have tested in separate programs in which the niobium was concentrated in nodules. In those alloys, which were tested at only 1110°F (600°C), the niobium was aggressively attacked by sulfur either from the SO_2 in the gas stream or from condensed sulfates in the ash. Table 2-8 shows the spot analysis of the oxide layer and zones of oxidation within the alloy. The samples will be sent to UTRC for further metallurgical testing.

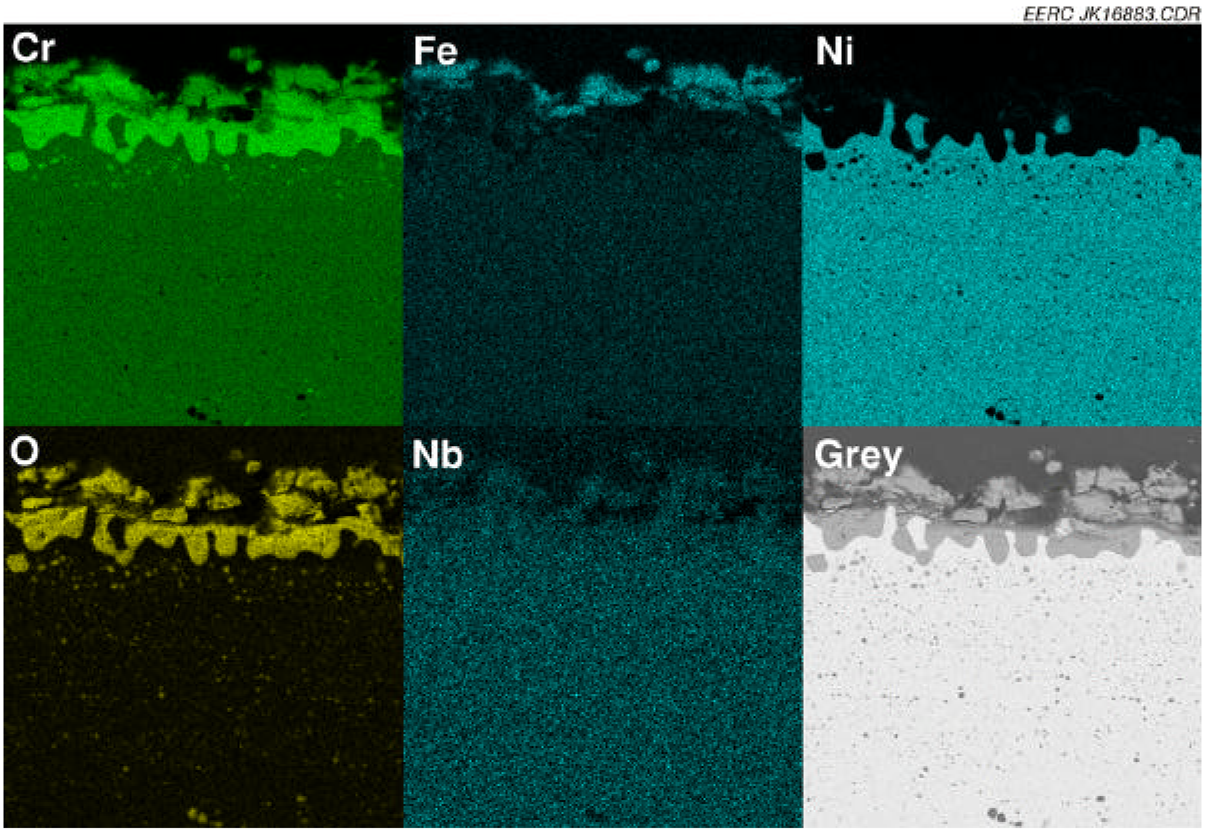

Exhibit 2-30
X-Ray Maps of Alloy MA-754

The low sulfur and slag attack on MA 754 is partially due to the excellent chemical resistance of the alloy, but also to the temperature at which it was tested. As stated at the beginning of this section, previous sampling and analysis of deposits from full-scale boilers (Hurley and Benson, 1995) has shown that sulfur is not thermodynamically stable as a condensed sulfate in the presence of coal ash at temperatures above approximately 2000°F (1090°C). This is why no condensed sulfates were used in the surface ash coating for this test, even though they are added when testing at lower temperatures. In addition, at 2100°F (1150°C), the slag does not flow, but instead sinters into a hard mass that has low corrosivity because of the low diffusion rates of corrodents through the high-viscosity material. Also, the sintered slag should reduce the attack of the alloy by gas-phase species.

Table 2-8
Elemental Concentrations of the Oxidation Products, wt%

Element	Surface Oxide Layer			Oxidation Zone Within the Alloy		
Cr	81.6	77.0	78.2	63.5	43.2	76.8
O	15.7	15.2	36.1	13.6	8.9	15.7
Fe	0.0	2.8	3.0	0.0	0.2	0.3
Ni	<0.1	1.2	1.4	10.1	39.5	0.9
Ti	1.8	0.9	1.1	3.6	1.8	2.7
Al	0.3	0.7	0.7	7.6	3.7	0.9
Ca	0.3	0.3	<0.1	<0.1	0.0	<0.1
Nb	0.0	1.0	0.0	0.0	0.5	0.0
P	0.0	0.2	0.0	0.3	0.5	0.1
Zn	0.2	0.2	0.0	0.0	1.1	0.1

This behavior of coal ash may indicate a high-temperature window in which the heat exchanger can be exposed directly to the products of coal combustion without the intervening ceramic tiles in place. Ash impinging on the surface of the tubes at temperatures within the window would freeze into a sintered mass that may protect the alloy from corrosion. It would then build up to a thickness at which the temperature reaches a point where the slag would flow. Observations of the slag-coated water-cooled slag screen tubes indicate that once the refractory has eroded from the surface of the tubes, a constant layer of slag and refractory approximately ½ inch thick remains. Because of the much higher temperature of the alloy in the radiant air heater, the slag layer built up on the surface of the tubes should also be no thicker than ½ inch.

Operating the radiant air heater without the ceramic tiles in place would allow the heat flow rate to the high-pressure air to dramatically increase. This would greatly reduce the required size of the heat exchanger and also greatly simplify its design, making it much less expensive to construct. It would also significantly increase the RAH heat recovery rate and decrease the size necessary to achieve the required process air temperature. Therefore, we propose that for the last SFS test of the present program, we remove the ceramic tiles from the flame side of the RAH and test its operation within this temperature window. Measurements will be made of the heat flow rate into the process air, and we can then also determine if there are any problems associated with slag flow when the RAH is operated in this configuration.

Bench-Scale Refractory Corrosion Testing

During this quarter, four alumina-based castable refractory materials from Plibrico and ALCOA were tested in the DSAF using MRYS lignite slag. The first castable is from Plibrico, Plicast 90 MAV. It contains approximately 10% magnesium–aluminate spinel and 90% alumina. The remaining three are from ALCOA. The second castable contains 12% magnesium aluminate spinel, SFL214AB3; the third contains 29% magnesium–aluminate spinel, SFL224AB3; and the fourth is an all-alumina self-flowing castable made with Alphabond 300, an experimental cement produced by ALCOA, AFL204AB3.

The blocks were prefired to 1625°C (2957°F) then tested at 1500°C (2732°F) using MRYS slag. The feed rate was approximately 50 grams per hour per injector. Exhibit 2-31 is a plot of the average measured recession versus time for the four samples. Since the rate of recession was so rapid for all four samples, the tests were stopped early. Exhibit 2-32 is a photograph of the samples from ALCOA after testing with MRYS lignite slag. Exhibit 2-33 is a photograph of Plicast 90 after testing with MRYS lignite slag. As compared to the all-alumina Plibrico castables tested previously with the MRYS slag, the castables tested this quarter behaved marginally better, in that they did not swell and crack as did the earlier samples. However, corrosion rates with the lignite slag are far too rapid for the new samples, so none are recommended for use in a slagging combustion system firing a lignite. In future tests, all four castables will be tested with Illinois No. 6 slag at 1500°C (2732°F) to compare the recession rates with the other castables tested in the DSAF. The DSAF was also used this quarter to fire slag taps to 1625°C (2957°F), for the SFS combustor.

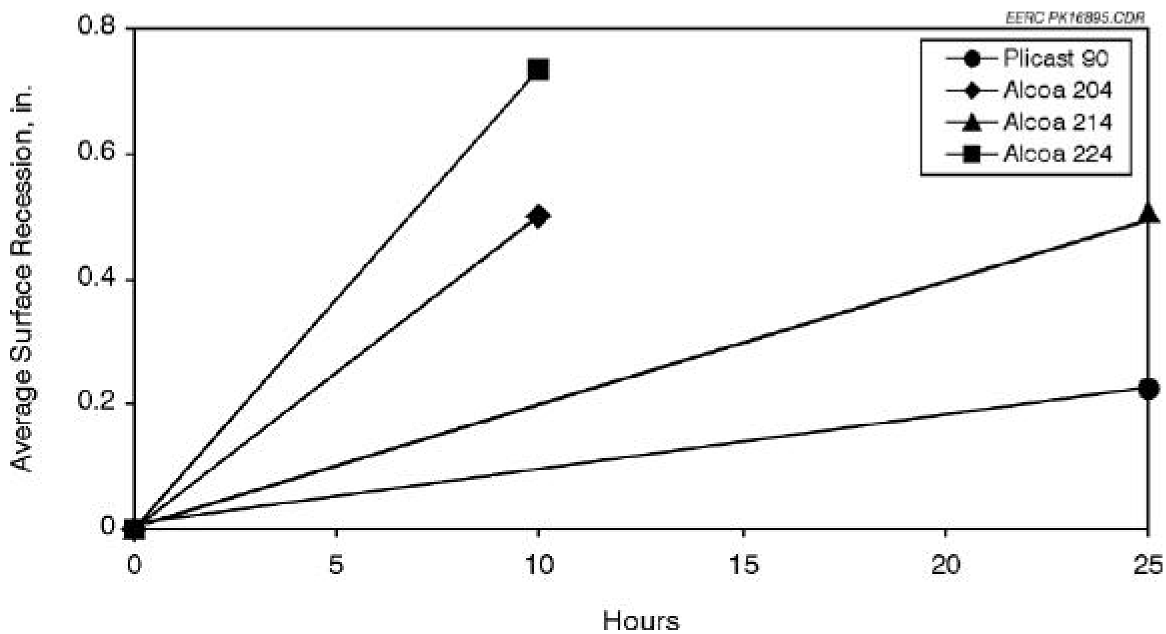

Exhibit 2-31
Plot of Recession Versus Time for Castable Materials After Dynamic Corrosion Test Using MRYS Lignite Slag

EERC PK16896.CDR

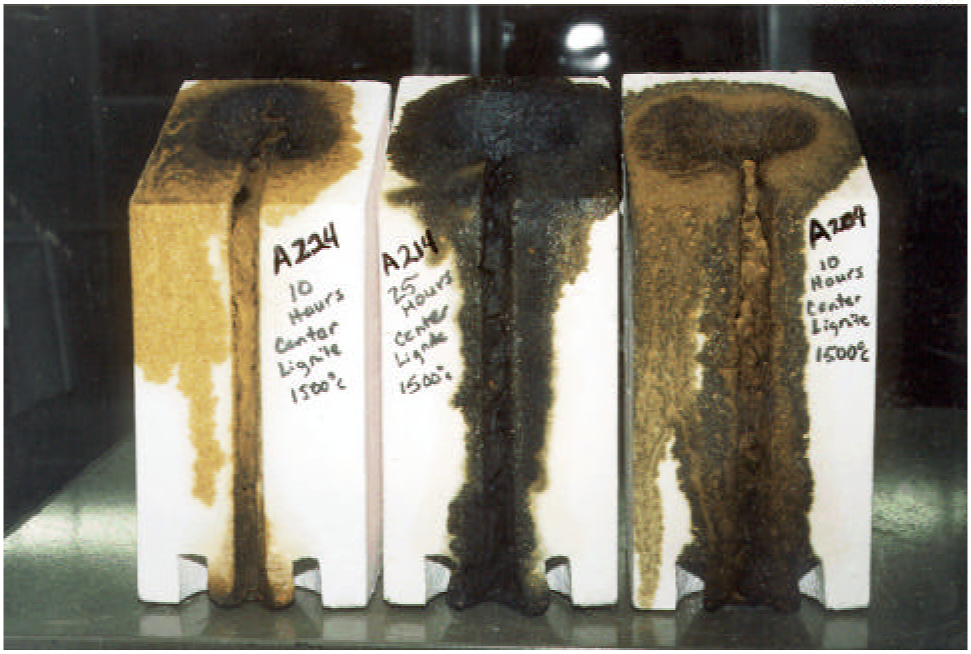

Exhibit 2-32
Photograph of ALCOA Samples After Dynamic Corrosion Test Using MRYS Lignite Slag. A224 = SFL224AB3, A214 = SFL214AB3, A204 = SFL204AB3

EERC PK16897.CDR

Exhibit 2-33
Photograph of Plicast 90 After Dynamic Corrosion Test Using MRYS Lignite Slag

References

Hurley, J.P.; Benson, S.A. Ash Deposition at Low Temperatures in Boilers Burning High-Calcium Coals: 1. Problem Definition. *Energy and Fuels* **1995**, *9*, 775–781.